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WATER QUALITY

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March 4, 2011

BP Products North America Inc.
2815 Indianapolis Blvd.
P O Box 710
Whiting, IN 46394-0710

Mr. Paul Higginbotham
Indiana Department of Environmental Management
Office of Water Quality – Permits Branch
100 N. Senate Avenue
Mail Code 65-42
Indianapolis, IN 46204-2251

Subject: BP Whiting Business Unit 316 (a) Phase I Thermal Effluent Study Report

Dear Mr. Higginbotham:

Please find enclosed our Phase I report which is part one of our revised Thermal Study Plan submitted and approved by IDEM on August 31, 2010. This Phase I report includes the delineation of the thermal plume based on field data and numerical modeling.

Based on the thermal plume study results, an updated 316(a) variance demonstration is needed. BP will prepare a proposed 316(a) variance demonstration (Phase 2) plan in response to IDEM's comments and seek IDEM's approval. Once IDEM approves, BP will implement the Phase 2 biological study in the summer of 2011. This demonstration would update the 1975 variance study and be submitted along with the 2012 NPDES permit renewal application.

Please contact Rose Herrera (219) 473-3393 if you have any questions regarding this report.

Sincerely,

Linda Wilson

Linda J. Wilson
Environmental Manager
Whiting Business Unit

Attachment

Copy:
Steve Roush, IDEM Office of Water Quality Permits Branch.
Jim Stahl, IDEM Office of Water Quality

AECOM Environment

Prepared for:
BP Products North America, Inc
Whiting Refinery

Prepared by:
AECOM
Warrenville, IL
February 2011

BP Whiting Refinery Thermal Plume Study
BP Products North America, Inc

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BP Whiting Refinery Thermal Plume Study
BP Products North America, Inc

Prepared By Matt Hodge, Lead Modeler

Prepared By Josh Giovannetti, Field Survey Lead

Reviewed By Brian O'Neil, Sr. Technical Reviewer

Reviewed By Ben B. Zhang, Project Manager

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Executive Summary

The BP Whiting Refinery is located in Whiting, Indiana, on the southern shore of Lake Michigan between Calumet and Indiana Harbors. The Facility uses once-through cooling water (OTCW) drawn from two intakes located approximately 1,200 feet offshore in Lake Michigan. NPDES Permit (No. IN0000108) was issued by Indiana Department of Environment Management (IDEM), effective August 1, 2007, authorizing BP Whiting Refinery to discharge non-contact once-through cooling water to Lake Michigan through Outfall 002. The currently permitted monthly average daily heat load limit is $1.7x10^9$ BTU/hr and daily maximum heat load limit is $2.0x10^9$ BTU/hr. The outfall is located in a small bay in Lake Michigan to the east of the Lakefront Wastewater Treatment Plant (WWTP).

Based on a joint Clean Water Act (CWA) Section 316(a) thermal demonstration study conducted by Union Carbide and BP (formerly Amoco) in 1975, thermal effluent limitations were granted in the 2007 NPDES permit. Part III of the permit requires that BP submit an updated316(a) variance request with the next NPDES permit renewal application due in February 2012. BP prepared a Whiting Refinery Thermal Effluent Thermal Study Plan and submitted the Plan to IDEM for review in July 2010. The plan described the proposed methodology to be used for the thermal plume and 316(a) variance studies to fulfill the requirement in the NPDES permit. A phased approach to the study was agreed by IDEM and BP. Phase 1 would conduct a thermal plume study and Phase 2 would develop a 316(a) variance demonstration if needed. This report documents the activities of the Phase 1 thermal plume study and findings.

According to the approved thermal plume study plan, BP conducted a four-week long field survey in the receiving water near Outfall 002 from September 23 to October 27, 2010. EFDC modeling software was used for the development of the thermal model due to the complex hydrodynamics of the BP Whiting thermal discharge and the need to evaluate the thermal plume in three dimensions. In addition, the CORMIX model was used to provide a preliminary estimate of the extent of the thermal mixing zone and to define the extent of discharge induced mixing. This information was used to define the study domain for the EFDC model.

The calibrated and validated model was used to predict the extent of the thermal plume under a range of worst-case scenarios. The worst case scenarios include summer time (warm) conditions and spring time (cool) conditions. The two seasonal variations were evaluated under both north-northwest ambient water currents and south-southeast ambient water current conditions. The same scenarios were evaluated for the existing configuration of the BP Whiting plant and for the proposed future configuration.

The results of model scenario runs indicate that the thermal plume extends beyond the 1,000-foot arc encircling the outfall under worst-case scenarios. The proposed future plant conditions are not expected to have any significant impacts on the extent of the thermal plume. The extent of the thermal plume is greatest when wind is from the north and ambient current directions are towards the southeast.

1.0 Introduction

BP Products North America, Inc, and its contractor AECOM, submitted a Thermal Effluent Study Plan (the Plan) to Indiana Department of Environmental Management (IDEM) during the summer of 2010 and IDEM comments were received on August 13, 2010. The Plan presented a thermal effluent study plan designed to characterize the potential impacts of the thermal discharge of the BP Whiting Refinery in Whiting, Indiana (the Facility). Issued by IDEM in June 2007, NPDES Permit (No. IN0000108) authorizes BP Whiting Refinery to discharge non-contact cooling water to Lake Michigan through Outfall 002. The current monthly average daily heat load limit is 1.7×10^9 BTU/hr and daily maximum heat load limit is 2.0×10^9 BTU/hr.

Based on a joint 316(a) thermal demonstration study submitted by Union Carbide and BP (formerly Amoco), thermal effluent limitations were granted in 1975. Part III of the permit requires that BP submit a new 316(a) variance request with the next NPDES permit renewal application. This document summarizes the thermal plume study BP performed on its Outfall 002, once-through cooling water effluent, to satisfy the NPDES permitting and IDEM regulatory requirements. This study was designed to characterize the impact of the thermal discharge from the BP Whiting Refinery Outfall 002.

The Plan outlined a two phase approach to satisfy Part III of the NPDES permit. Phase 1 included the delineation of the thermal plume based on field data and numerical modeling. The thermal plume would then be evaluated for compliance with current thermal water quality criteria as outlined in Section 1 of the Plan. According to the Indiana minimum surface water quality criteria governing temperature in Lake Michigan, the receiving water temperature cannot be 3 F greater than existing background temperatures outside of a 1,000-foot arc encircling the thermal discharge. In addition, the receiving water temperature outside the arc cannot exceed maximum monthly temperatures prescribed for Lake Michigan (as described in Section 5.2 in more detail), except when exceedance has been caused by the intake water temperature. If the thermal plume met the current thermal criteria, no further analysis would be required; however, if thermal criteria were not met, a 316(a) variance demonstration would be performed in Phase 2. If a Phase 2 316(a) demonstration was determined to be required, BP would submit a proposed Phase 2 plan to IDEM for review and approval based on IDEM's comments (dated August 13, 2010) on the original 316(a) variance plan. BP would then submit its 316(a) demonstration application in conjunction with their NPDES permit renewal application 180 days prior to the date of permit expiration (July 31, 2012).

This document focuses on the execution of Phase 1 of the Plan and a summary of results. The size, areal extent, and depth of the thermal plume were characterized by both a numerical modeling study and a field survey under a range of weather conditions and thermal loading scenarios up to the monthly average daily heat load limit (1.7×10^9 BTU/hr). For the purposes of this study, the thermal plume was considered to be the area where water temperatures were three degrees Fahrenheit or more above ambient conditions. The following provides a summary of field data collection and model development, including model calibration and validation. The calibrated and validated model provided a characterization of the thermal plume under a range of extreme weather conditions for existing and proposed plant thermal loading scenarios. Finally, the predicted extent of the thermal plume was compared against water quality criteria as outlined in the Plan.

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2.0 Thermal and Current Field Survey

2.1 Field Survey Objective

In accordance with Phase 1 of the BP Whiting Thermal Effluent Study Plan, a field study was performed to characterize hydrodynamic and thermal behavior in the southern Lake Michigan embayment near the BP Whiting Refinery. This study was part of thermal analysis to comply with the thermal effluent requirement prescribed in NPDES Permit No IN0000108. The data collected during the field study was used for the development, calibration, and validation of a hydrodynamic numerical model.

2.2 Field Survey Design

IDEM reviewed the BP Whiting Thermal Effluent Study Plan and provided comments in a letter dated August 13, 2010. This letter included comments on the Phase 1 thermal field study design specifically, instrumentation placement and deployment timing and length. BP discussed these comments with IDEM during a conference call on August 24, 2010. During the call, a study design was agreed upon and summarized in the response to comments letter (the Letter, Appendix A). The approved study design included the following:

1. An initial reconnaissance-level survey of Lake Michigan was conducted near the BP Whiting facility to characterize the location and extent of the thermal plume as well as the depth of water at each of the proposed mooring locations.
2. Measurement of water temperature at 13 locations within the embayment. Thirteen thermistor moorings were deployed and programmed to record temperature values at approximately 15 minute intervals and left in place for 28 days.
3. Measurement of water current velocity through the water column in the embayment to collect data used in model calibration. Two upward-facing Acoustic Doppler Current Profilers (ADCPs) were deployed in the embayment for collection of current velocity data. The ADCPs were left in place for 28 days and were programmed to record water velocity at approximately 15-minute intervals.
4. Boat-based surveys to provide a spatially detailed picture of the thermal plume during a single day and to supplement the mooring data. Two boat-based surveys were conducted during deployment following the deployment and prior to mooring retrieval.

2.3 Data Collection

2.3.1 Reconnaissance

The reconnaissance survey of the study area was completed on August 30, 2010. During the reconnaissance, a boat traversed the study area along the transects depicted in Figure 2-1. Attached to the boat, out of influence of vessel wake, was an In-Situ Level TROLL 500 thermistor and Odom Hydrographic Hydrotrac echo sounder taking samples every two seconds. A slow rate of boat speed was maintained to aid in data quality and a Trimble GeoXH GPS unit with external Zephyr antenna mounted on a range pole was used to tie in data locations (See Appendix C for photo). Additional arcs not defined in the Letter were transected in order to increase data coverage. The data were used to obtain a preliminary characterization of temperature and bathymetry within the study area. This information was also used to finalize mooring locations and mooring configurations.

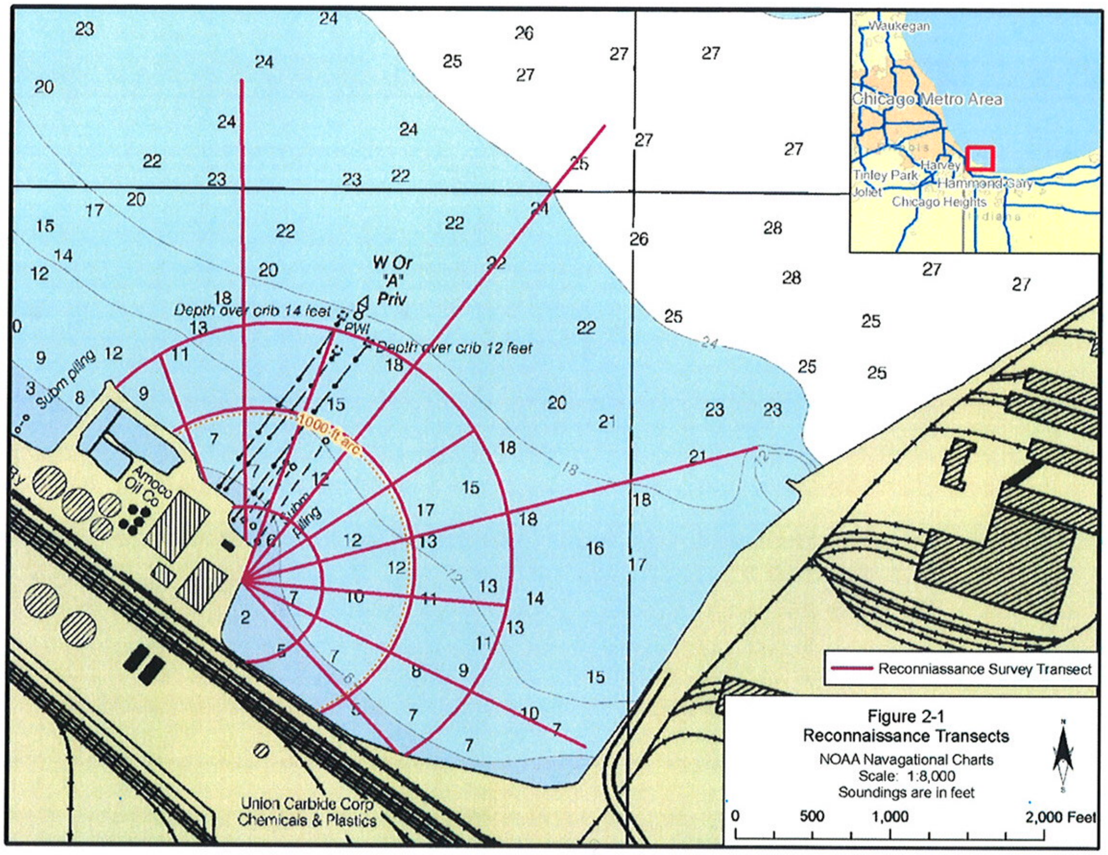

Figure 2-1. Reconnaissance Survey Transects

2.3.2 Thermistor Mooring Deployment

The following section describes the setup and deployment of recording instrumentation within the southern Lake Michigan embayment. Nexsens T-Nodes and Submersible Data Logger instruments were moored in 13 separate arrays in the vicinity of the BP Whiting Refinery outfall (Figure 2-2, Table 2-1) and configured with cellular telemetry, or wireless transmission (See Appendix C for photo). Deployment of the mooring arrays was completed on September 23, 2010 and retrieval was initiated on November 2, 2010. The deployment procedure consisted of locating each prescribed GPS location, testing depth with a hand held depth sounder, adjusting location slightly until depth properly corresponded with mooring configuration, and carefully deploying mooring as to not damage equipment. Retrieval consisted of locating each mooring surface buoy and carefully loading the mooring on the boat as to not damage equipment.

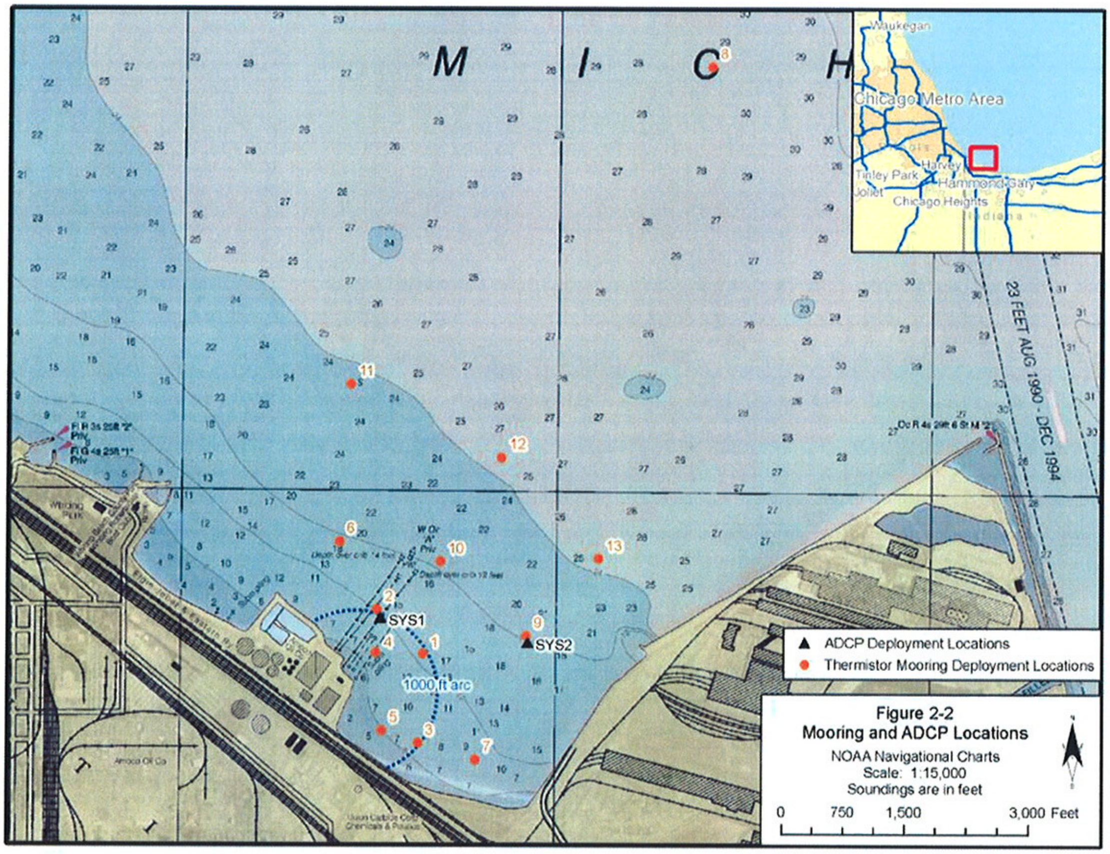

Figure 2-2. Mooring and ADCP Deployment Locations

The general configuration for the mooring arrays is shown in Figure 2-3. Each of the temperature sensor arrays consisted of a surface buoy which contained the data logger, cellular telemetry antenna, and modem. Below the buoy, the thermistors were attached to a guide cable which spanned the depth of the water column. The top-most thermistor was attached below the buoy approximately 3 feet from the water surface. The bottom-most thermistor was attached approximately 3 feet from the bottom of the guide cable. The remaining thermistors were attached at equal intervals between the top- and bottom-most thermistors, totaling 2 to 6 thermistors per mooring as indicated on Table 2-1. At the bottom of the guide cable, approximately 10 feet of heavy chain was placed prior to the pyramid anchor in order to absorb waves and fluctuations in water depth.

Table 2-1. Mooring Array Deployment Configuration and Location

ID	Mooring Type	Easting (ft)	Northing (ft)	Water Depth (ft)	Number of Thermistors
SYS1	Current	2,845,917	2,342,695	12	--
SYS2	Current	2,847,702	2,342,400	18	--
TM01	Temperature	2,846,430	2,342,258	13	3
TM02	Temperature	2,845,873	2,342,796	16	4
TM03	Temperature	2,846,372	2,341,177	5	2
TM04	Temperature	2,845,863	2,342,269	13	4
TM05	Temperature	2,845,939	2,341,325	5	2
TM06	Temperature	2,845,414	2,343,616	20	5
TM07	Temperature	2,847,069	2,340,974	5	2
TM08	Temperature	2,849,899	2,349,381	31	6
TM09	Temperature	2,847,681	2,342,477	17	4
TM10	Temperature	2,846,634	2,343,379	23	5
TM11	Temperature	2,845,546	2,345,518	27	5
TM12	Temperature	2,847,373	2,344,639	26	5
TM13	Temperature	2,848,554	2,343,419	26	5

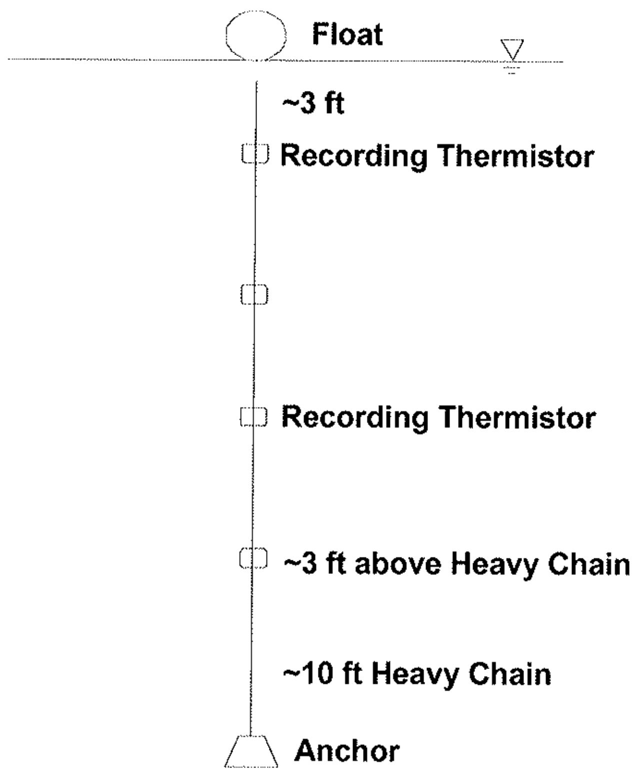

Figure 2-3. General Mooring Diagram

2.3.3 ADCP Deployment

Two Teledyne RD Instruments Workhorse Sentinel Acoustic Doppler Current Profilers (See Appendix C for Photo) were deployed at two separate locations (SYS1 and SYS2) within the embayment (Figure 2-2, Table 2-1) on September 27, 2010. The ADCPs were deployed in bottom-mounted seabed frames, positioning the ADCPs facing upward and approximately 2.5 feet above the lake bottom. Both instruments were set up to record a data ensemble every 15 minutes. Calibration and sampling were initiated in a controlled laboratory environment prior to arrival in the field. The ADCPs were set to record in 5 separate bins, providing information for 5 separate layers of the water column. Sonardyne Release Transponders with buoys were attached to the frames for location and retrieval in order to eliminate surface expression interference with the ADCPs. Retrieval was performed on October 25, 2010.

2.3.4 Boat-Based Surveys

Two boat-based surveys were conducted for the field study; one immediately after all equipment was deployed on September 27, 2010, and one immediately before equipment was retrieved on November 2, 2010. Conductivity, temperature, and depth were taken throughout the water column at 14 locations on the first survey and 19 locations on the second survey using an In-Situ Troll 9500 multi-parameter probe. Locations of boat-based survey are shown in Figure 2-4. These data were used to supplement and cross-check the mooring array data.

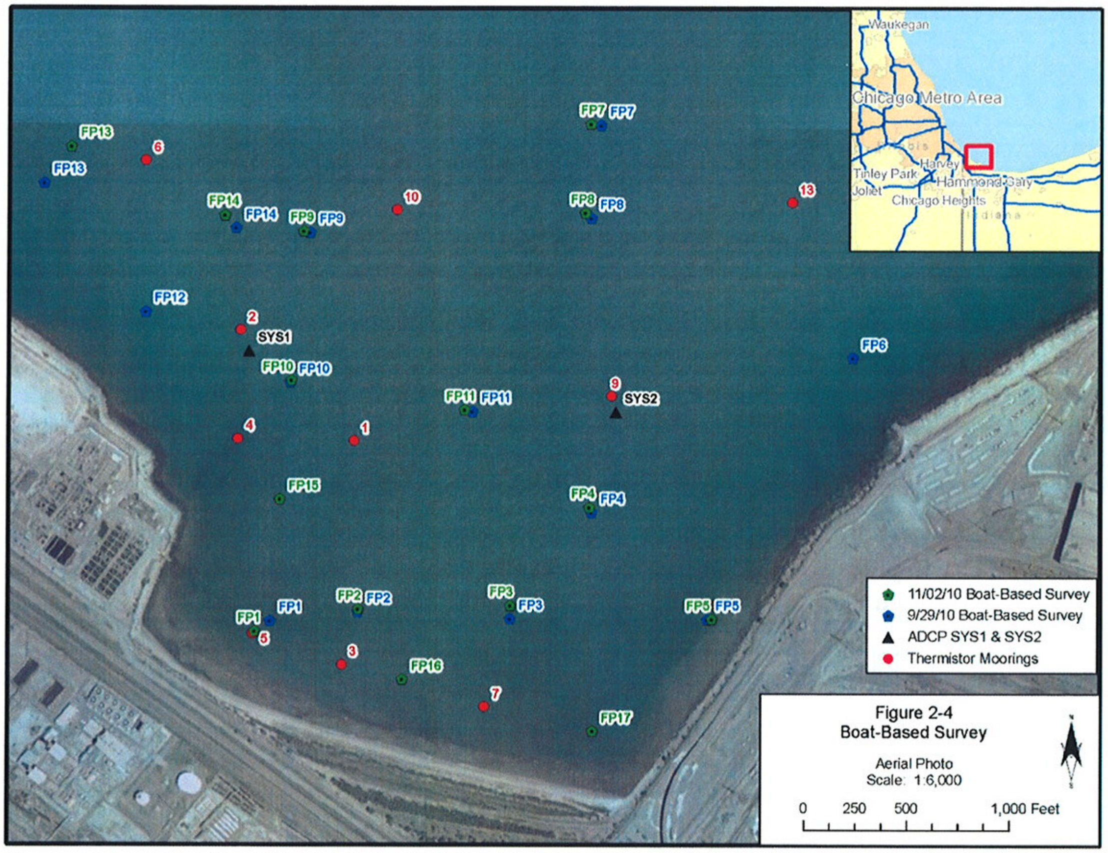

Figure 2-4. Boat-Based Survey Locations

2.4 Data Analysis

2.4.1 Weather Conditions during Field Deployment

Weather conditions that occurred during the field deployment are shown in Figures 2-5 and 2-6. Winds mainly came out of the west, south-southwest and north. These conditions were similar to historical conditions as can been seen on Figure 2-7 (See Appendix C for Photo), with stronger winds mostly coming out of the south-southwest. The maximum hourly wind average observed during the deployment period was approximately 44 knots, coming out of the west-southwesterly direction. From 2005 to 2010, the maximum hourly wind average observed was approximately 48 knots out of the south. As seen in Figure 2-6, a variety of air temperature conditions were captured during the field deployment period. Deployment was performed during fall when temperatures are steadily dropping towards winter. While this allowed for a good range of air temperatures to be observed, it did not allow for observation of extreme highs or lows.

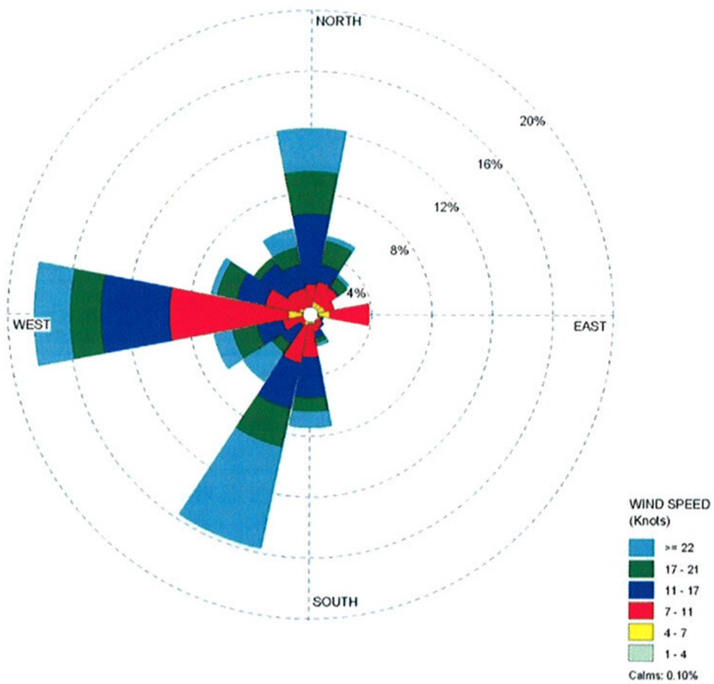

Figure 2-5. Wind Rose for Deployment Period (Frequency a given speed blows from each direction)

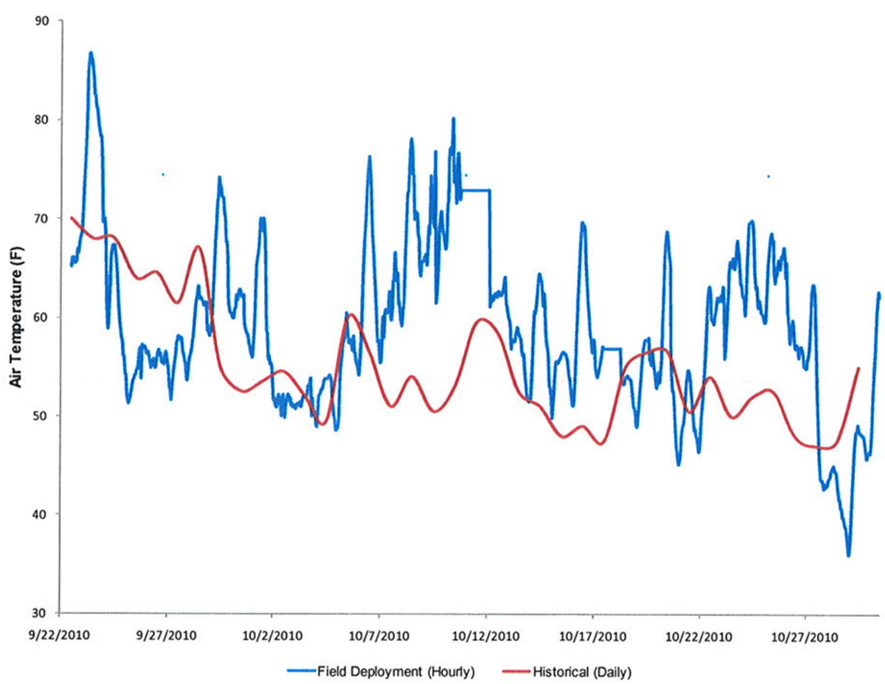

Figure 2-6. Hourly Deployment vs. Daily Historical Air Temperature for the Deployment Period

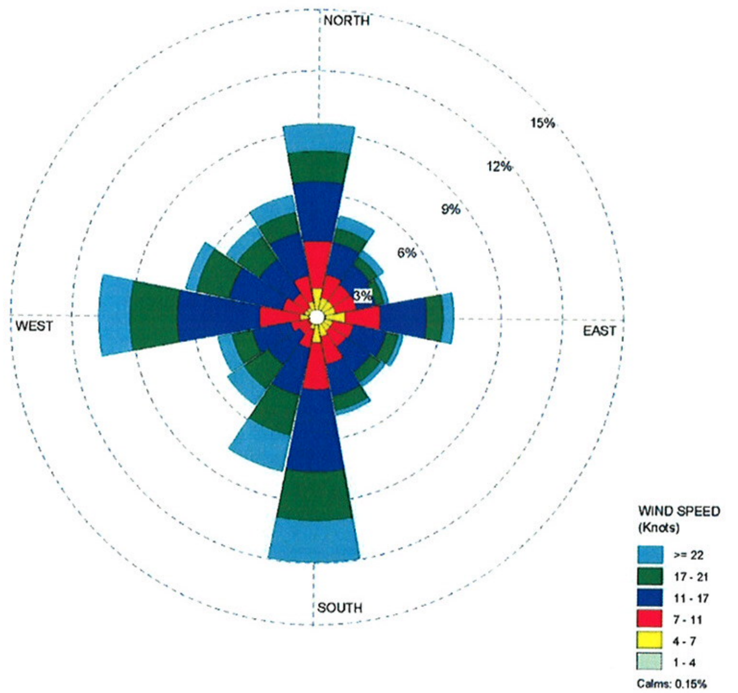

Figure 2-7. Historical Wind Rose for 2005-2010 (Frequency a given speed blows from each direction)

2.4.2 Refinery Usage Conditions During Field Deployment

Refinery water intake and discharge conditions during the field deployment are shown in Figure 2-8. Refinery discharge flow from Outfall 002 ranged from 67 to 80 million gallons per day. Intake temperatures ranged from 54 to 68 F and discharge temperatures ranged from 79 to 93 F. The dropping fall season air temperature influence on water temperature is evident in both intake and discharge temperatures. Based on these data, the average heat load observed during the deployment period was approximately 6.8 x 10^8 BTU/hr, well below the monthly average permit limit of 17 x 10^8 BTU/hr.

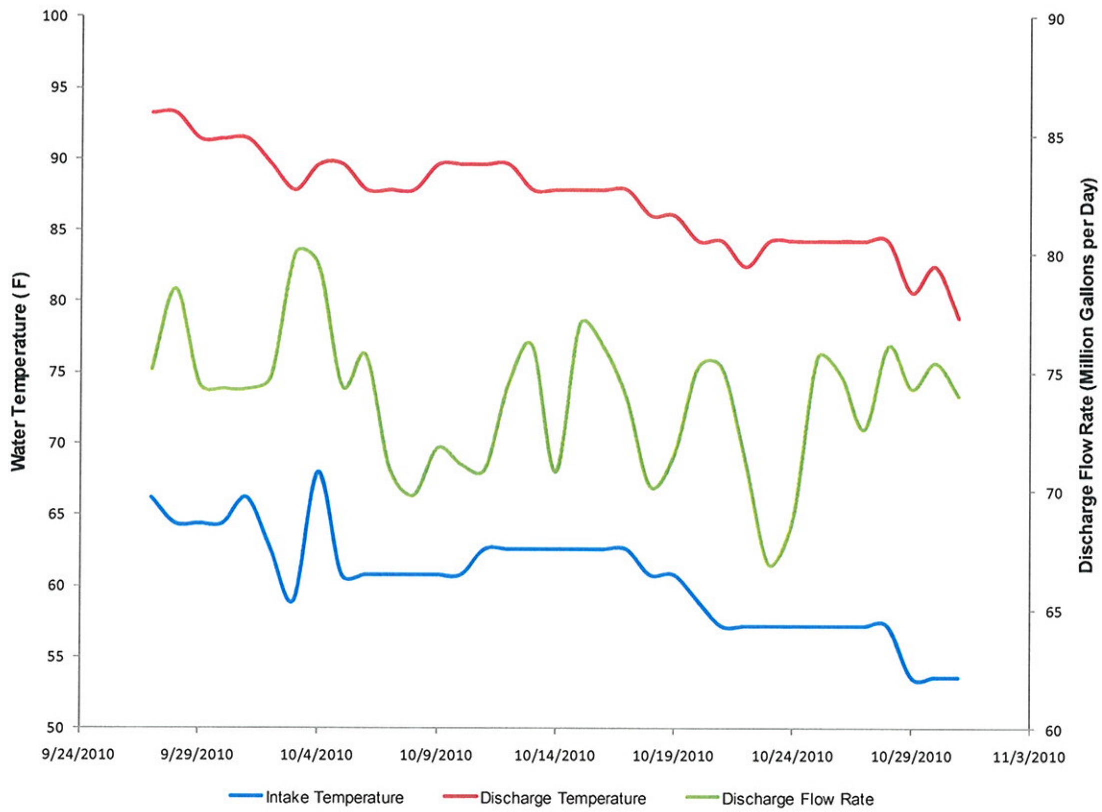

Figure 2-8. Plant Operations During Field Data Collection

2.4.3 Reconnaissance Survey

The reconnaissance survey provided an overview of the study area and location of the surficial thermal plume at a time close to the planned deployment. Figure 2-8 indicates the traversed transects with surficial (3 feet below the surface) temperature. In addition to the proposed transects, one additional arc was traversed in order to provide increased coverage as compared to Figure 2-1. Depth was also recorded as previously outlined in Section 2.3.1. These depth data were used to develop bathymetry contours as indicated in Figure 2-9. The depth data contours indicated some changes in bathymetry within the transect arcs that have occurred as compared to the 2003 NOAA Navigational Chart. This was especially evident along the shoreline. These changes were used in the model setup and to finalize thermistor array length and configuration. The entire survey spanned eight hours, so surficial temperatures would be expected to change throughout the day as indicated with the Figure 2-8 transect time stamps. The reconnaissance survey also provided valuable deployment and retrieval logistical information.

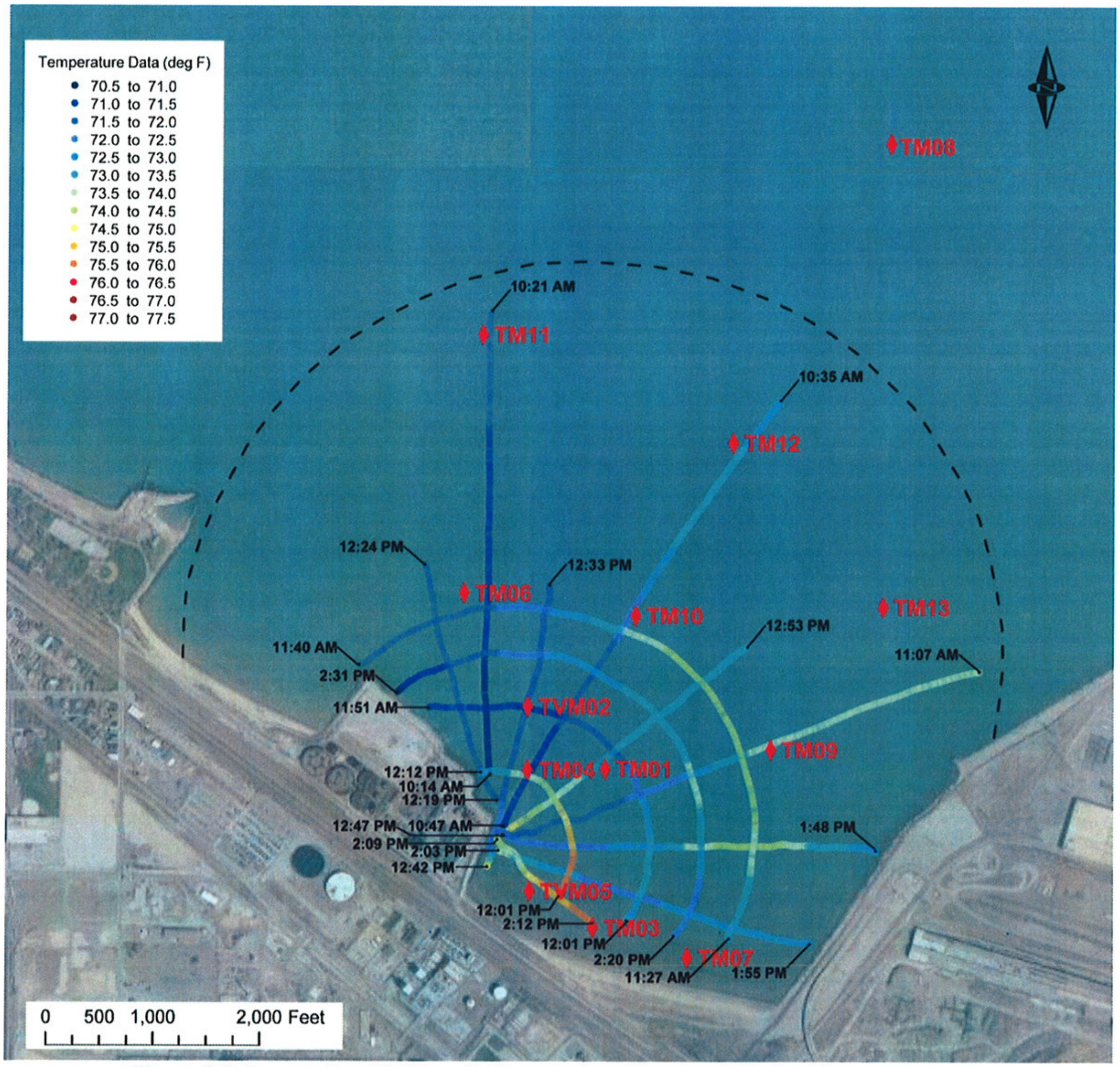

Figure 2-9. Transects with Discrete Temperature Traversed During Reconnaissance

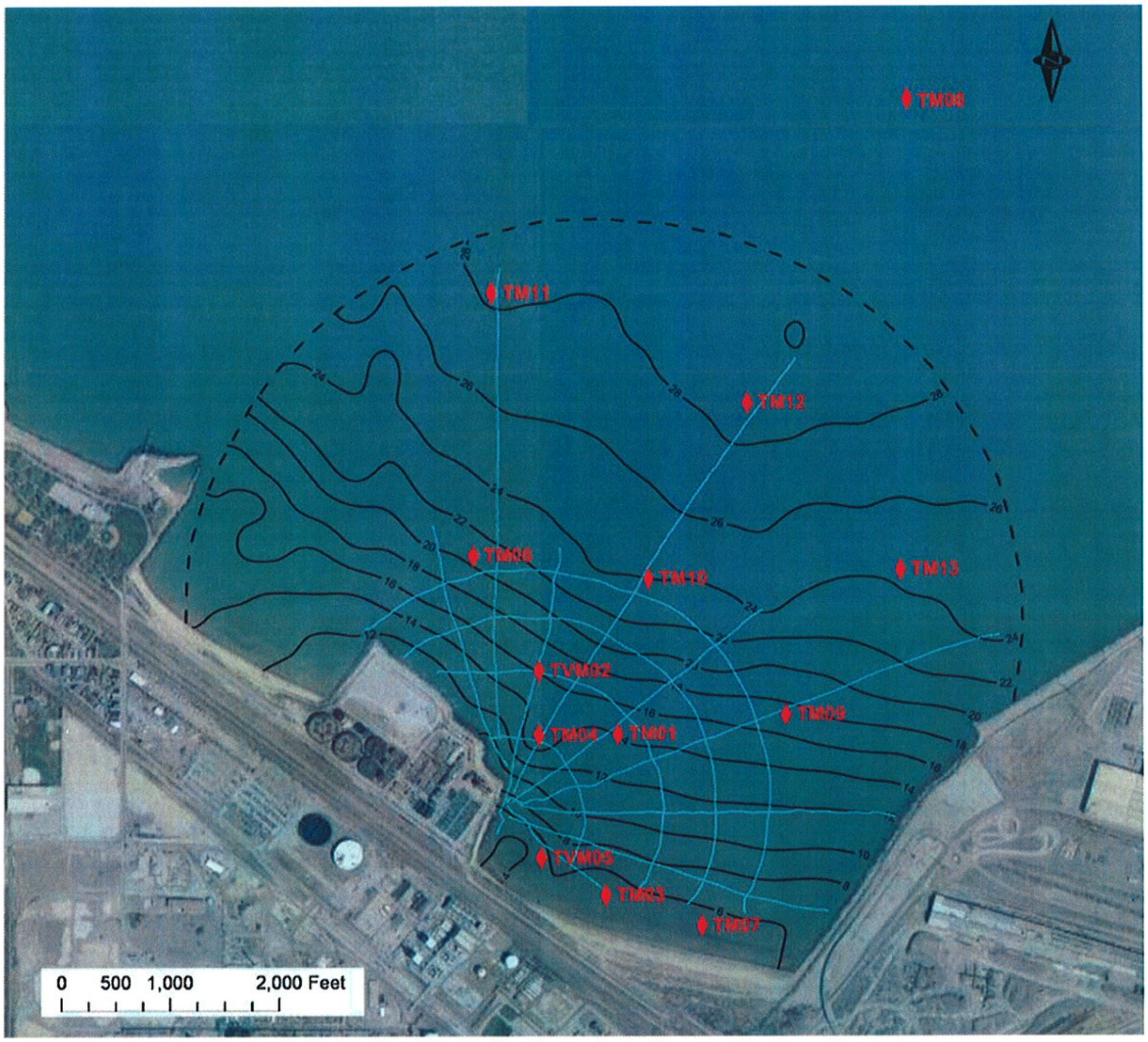

Figure 2-10. Bottom Depth Contours from Reconnaissance Survey

2.4.4 Current

Water currents were measured by the two ADCP moorings, SYS1 and SYS2, as located on Figure 2-2. Data for the entire deployment period was downloaded from both ADCP data loggers after retrieval. Current patterns directly influence the extent of the thermal plume. Consequently, an accurate representation of local currents is necessary for accurate predictions of the extent of the thermal plume. The Great Lakes Coastal Forecasting System (GLCFS) predicts hydrodynamic behavior in Lake Michigan, but the resolution of the GLCFS model is not sufficient to predict local current patterns at the scale required for this application. Therefore, observed data from SYS1 and SYS2 were important in the calibration and validation of the hydrodynamic model. Figures 2-10 and 2-11 display a depth-averaged current rose indicating the percent occurrence for direction water currents flow towards and velocity magnitude. Currents at SYS1 most often flow to the south southeast and also have the strongest magnitudes in that direction. Currents at SYS2 were more variable as flow direction was generally south to northeast; however, strongest currents flowed toward the east and northeast. This variation may be due to the fact that the location of SYS2 was closer to the peninsula which acts as a physical boundary, changing flow directions. These data indicate that most frequently during the deployment period, water current flowed counter clockwise from the northwest into the embayment where it flowed along the shoreline, leaving the embayment toward the northeast. Figures 2-12 and 2-13 display time series for depth averaged current direction and velocity during the deployment period. In agreement with Figures 2-10 and 2-11, SYS1 direction was much more consistent than SYS2. Both ADCPs indicate five periods of strong currents. During these strong current periods, SYS1 was predominantly flowing toward the southwest and SYS2 was predominantly flowing toward the northwest. This is consistent with the most frequent flow pattern previously described.

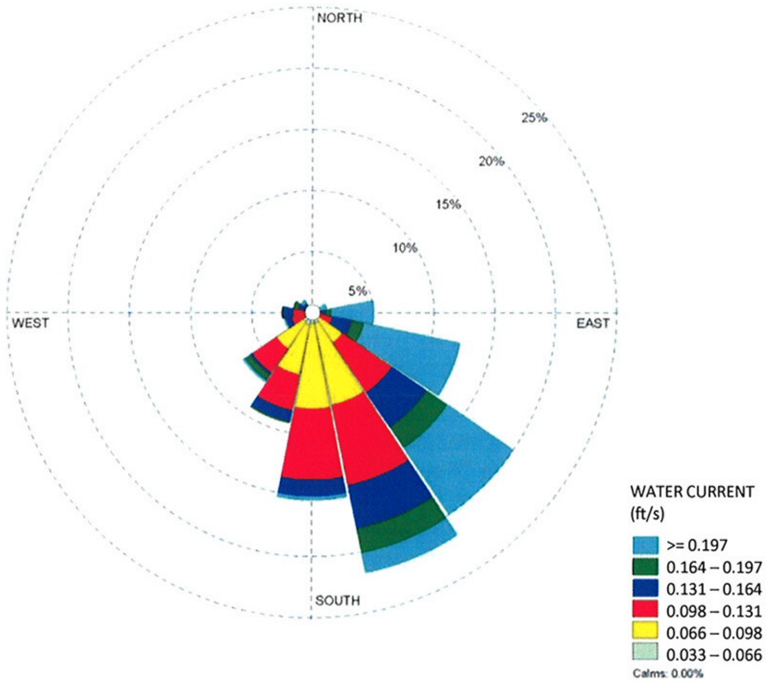

Figure 2-11. Current Rose for SYS1 ADCP (Frequency a given speed flows toward each direction)

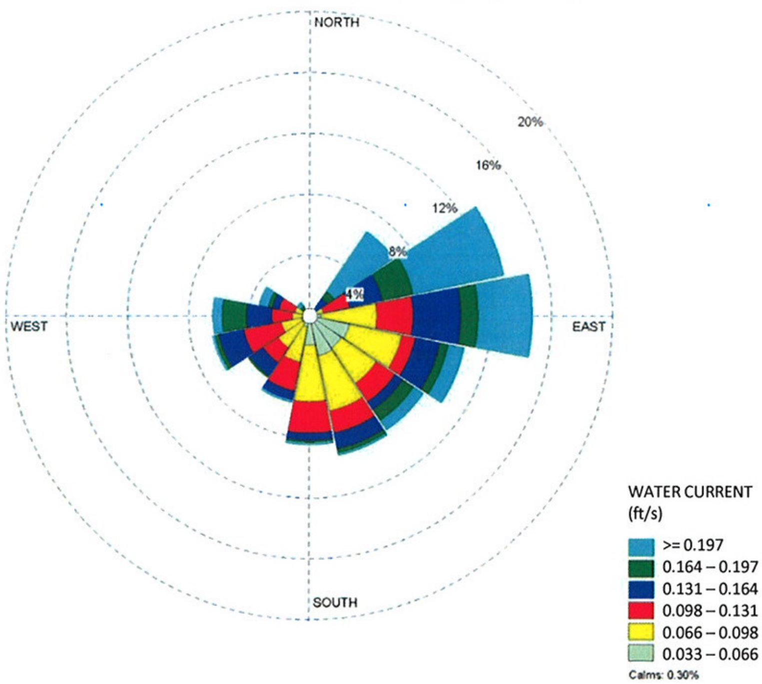

Figure 2-12. Current Rose for SYS2 ADCP (Frequency a given speed flows toward each direction)

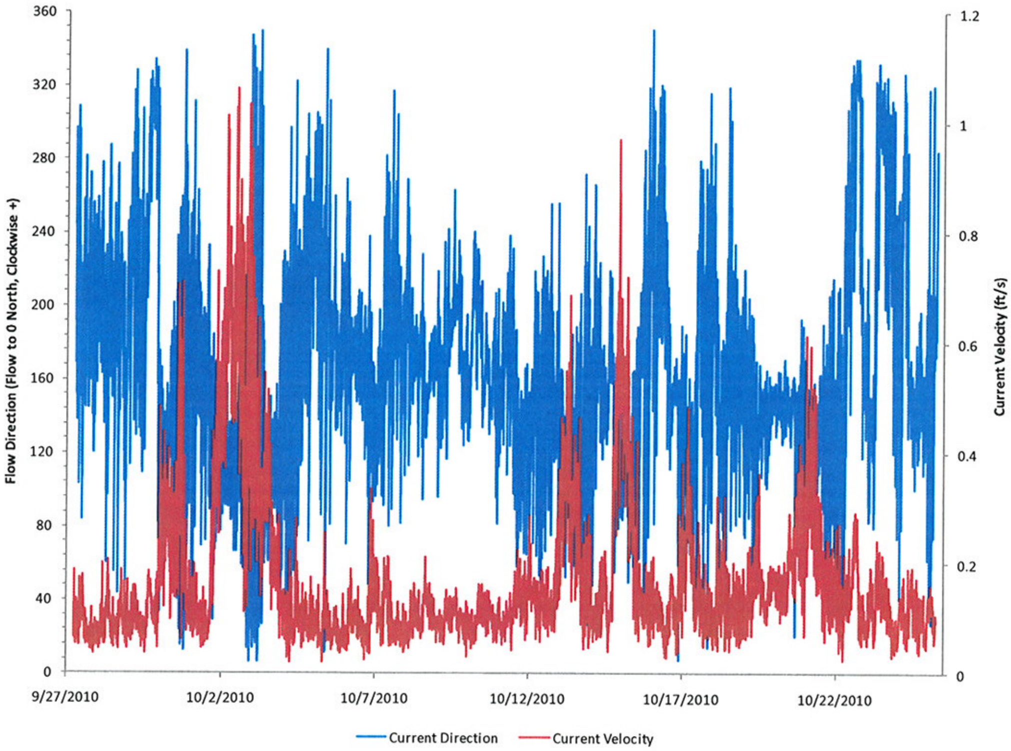

Figure 2-13. SYS1 Time Series of Direction and Velocity of Flow (Depth averaged)

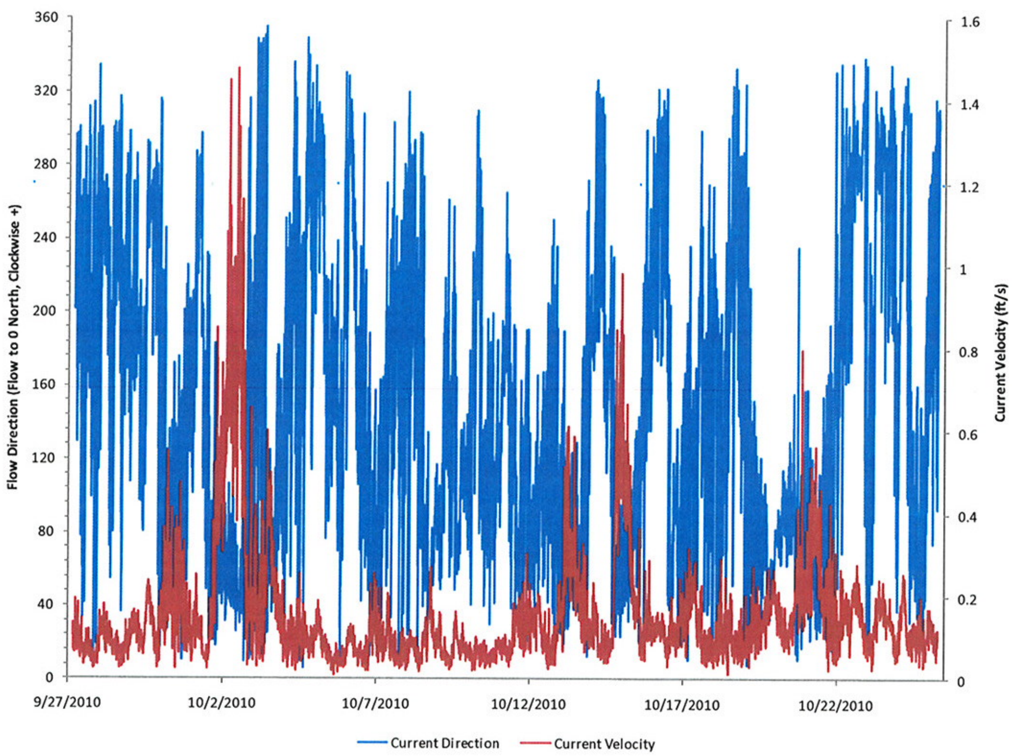

Figure 2-14. SYS1 Time Series of Direction and Velocity of Flow (Depth averaged)

2.4.5 Temperature

Water temperature data from all 13 moorings were downloaded daily via cellular telemetry. This allowed for quality control monitoring and an opportunity for expedient response to data logging issues. Typical to the fall season in southern Lake Michigan, two large storms occur during the deployment period, producing waves in excess of 10 feet. Three of the moorings located in very shallow water near shore (TM03, TM05 and TM07) experienced severe wave action at times. During severe wave actions, all three moorings developed an intermittent short circuit due to chafing on the bottom sand and resulted in recording errors. Once the shorts were identified during the next download and were addressed remotely by increasing the sampling frequency at these moorings to 5 minute intervals. More frequent recording increased the probability to capture representative temperature data between periods of short circuit. Table 2-3 shows a brief summary of mooring temperature data.

Table 2-2. Depth-Averaged Temperatures for Individual Moorings

Mooring Array	Depth-Averaged Temperature (F)			Standard Deviation
	Minimum	Maximum	Mean	Along Mooring Array
TM01	56.4	69.2	61.3	2.71
TM02	59.2	68.1	62.2	2.66
TM03	60.6	77.8	69.0	3.24
TM04	56.2	69.9	61.3	2.75
TM05	61.3	78.9	69.7	3.17
TM06	56.5	67.1	61.1	2.59
TM07	60.5	77.1	67.3	3.75
TM08	56.4	64.7	60.2	2.39
TM09	57.1	67.3	61.4	2.70
TM10	56.6	66.4	61.0	2.56
TM11	56.7	65.5	60.7	2.50
TM12	56.9	65.9	60.8	2.50
TM13	56.9	66.6	61.1	2.60

TM08 was located approximately two miles offshore to collect ambient condition data. This mooring had the lowest mean temperature and least variability throughout the water column. Temperature depth profile figures for individual moorings are included in Appendix B. Ambient water temperature was fairly constant around 64 F, peaking around October 2nd just above 65 F, before a dip below 60 F around October 4th. Temperatures slowly increased and became increasingly warmer at the surface as compared to the bottom of the water column until around October 14th. The water column became very well mixed for the duration of the study at the ambient location and slowly decreased to around 56 F toward the end of the deployment period.

As indicated from the depth averaged temperature Table 2-2, the moorings close to shore (TM03, TM05 andTM07) had the greatest mean temperatures over the study period. These moorings also had the greatest variability of temperatures throughout the water column. These moorings were located in the shallowest water, but they were also located in areas of likely discharge induced mixing from the outfall. In addition, current and wind observations would suggest that these three moorings were within the thermal plume for a significant amount of time. The maximum temperatures observed at moorings TM01, TM02 and TM04 would also suggest that they were within the thermal plume for some time; however, lower mean temperature values indicate that they were not within the plume for long periods of time. Moorings TM06, TM09 and TM10 were located in slightly deeper water (approximately 18 feet) and approximately 1,500 to 2,000 feet offshore. TM06 was most comparable to ambient conditions, whereas water temperature from TM10 over to TM09 became increasingly more variable throughout the water column. This suggests that TM09 may be influenced by a surficial thermal plume at certain times. The next set of moorings located approximately 3,000 feet offshore and in approximately 25 feet of water (TM11, TM12 and TM13) appeared to behave in a similar manner. To a lesser extent, TM13 may have been influenced by a surficial thermal plume. A subset of these data was used for model calibration and another for validation as further described in Section 3.

2.4.6 Data Quality Assurance

Thermistors were supplied with certified precision factory calibration. Each sensor has a unique quadratic equation employed to ensure accuracies for National Institute of Standards and Technology-traceable temperature measurements. Equipment was also spot-checked for temperature agreement with a calibrated thermometer prior to deployment. The Nexsens T-Node semiconductor thermistors have a range of 32 to 122 F and an accuracy of +/- 0.18 F. The deployment boat-based survey data was comparable to the mooring temperature. The average of temperature data from all mooring arrays and boat-based surveys was within 2.0 F.

The two ADCP units were set up prior to field deployment where the compass was calibrated in a controlled environment to an acceptable error of approximately 3 degrees. Velocity accuracy at the chosen settings was 0.3 percent of the water velocity relative to the ADCP (+/-0.001 ft/s). Post-data analysis included evaluation of the time series for consistency and interference.

The ADCP data and temperature data have been determined reasonable and complete for the deployment period of September 27 to November 2, 2010, and were representative of actual field conditions during this period. This assessment is based on three criteria:

1. There are no periods of multiple missing data points;
2. Data are internally consistent throughout the water column;
3. Data are consistent with other sources of data.

Figures 2-12 and 2-13 are graphs of the depth averaged speed and direction of the ADCP data for both SYS1 and SYS2. There are no blackout periods or data gaps during the 28 day deployment period. Additionally, Appendix B contains time series of each thermistor array temperature over time. Similarly, there are no thermistor data gaps during the deployment period. This demonstrates that both the ADCP and temperature data meet Criteria 1.

ADCP data, both SYS1 and SYS2, was analyzed vertically through the water column for the duration of the deployment. The vertical data was determined to be consistent within each ADCP system. Appendix B thermistor array time series also indicated that individual thermistors within each array follow similar temperature patterns. Within each array, some thermistors located nearer to the water surface demonstrate greater peaks than those located near the bottom of the water column. This is to be expected due to the possible presence of a floating thermal plume and the effects of solar radiation near the water surface. It can be concluded that the ADCP and temperature data meet Criteria 2.

Finally, simulated results from the Great Lakes Coastal Forecasting System (GLCFS; descriptive information provided in Section 3.3) were compared to the depth average current data from both SYS1 and SYS2. Good agreement was found for both ADCPs between the GLCFS output and observed data. Appendix B thermistor array time series indicate that all thermistor arrays follow the general temperature trend of the ambient array, except for TM03, TM05 and TM07. These three arrays are considered to be heavily influenced by the thermal plume and behaved very similarly to each other. This agreement between the independent, thirteen thermistor arrays demonstrates that the temperature data meet Criteria 3. Agreement of ADCP data and GLCFS model output demonstrates that the current data also meet Criteria 3.

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3.0 EFDC Modeling Setup and Calibration

This section describes the selection, set up, calibration, and validation of the numerical model of the thermal discharge into Lake Michigan to predict the extent of the thermal plume.

3.1 Model Selection

The model selected for characterization of the BP Whiting Refinery thermal discharge into Lake Michigan was EFDC (Environmental Fluid Dynamics Code). EFDC is a public-domain, finite-difference coupled hydrodynamics/thermal/water quality model supported by the USEPA (Hamrick 1996, Tetra Tech 2002). The version of EFDC that was used for this model was developed and is maintained by Dynamic Solutions.

EFDC can be applied in one, two, or three dimensions, depending on the nature and the complexity of the model domain. EFDC has been applied to a wide variety of environmental flow and transport problems, including salinity intrusion studies, power plant cooling studies, and discharge dilution studies. This model was selected to investigate the complex hydrodynamics of the BP Whiting Refinery thermal discharge and to evaluate the thermal plume in three dimensions.

3.2 Model Set Up

The model domain, boundary conditions, and mooring locations for calibration and validation of the model are shown in Figure 3-1. The model domain is a portion of Lake Michigan in the vicinity of Whiting, Indiana. The Cornell Mixing Zone model (CORMIX) was used as a screening level tool in order to determine the size of model domain necessary to capture the thermal plume. CORMIX is a USEPA approved model, but CORMIX does not have the capability to accurately predict thermal plume dimensions in complex environment like the one described in Figure 3-1. Based on the preliminary results from CORMIX, it was determined that a model domain that extended approximately 3 miles from the discharge location would be sufficient to capture the extent of the thermal plume.

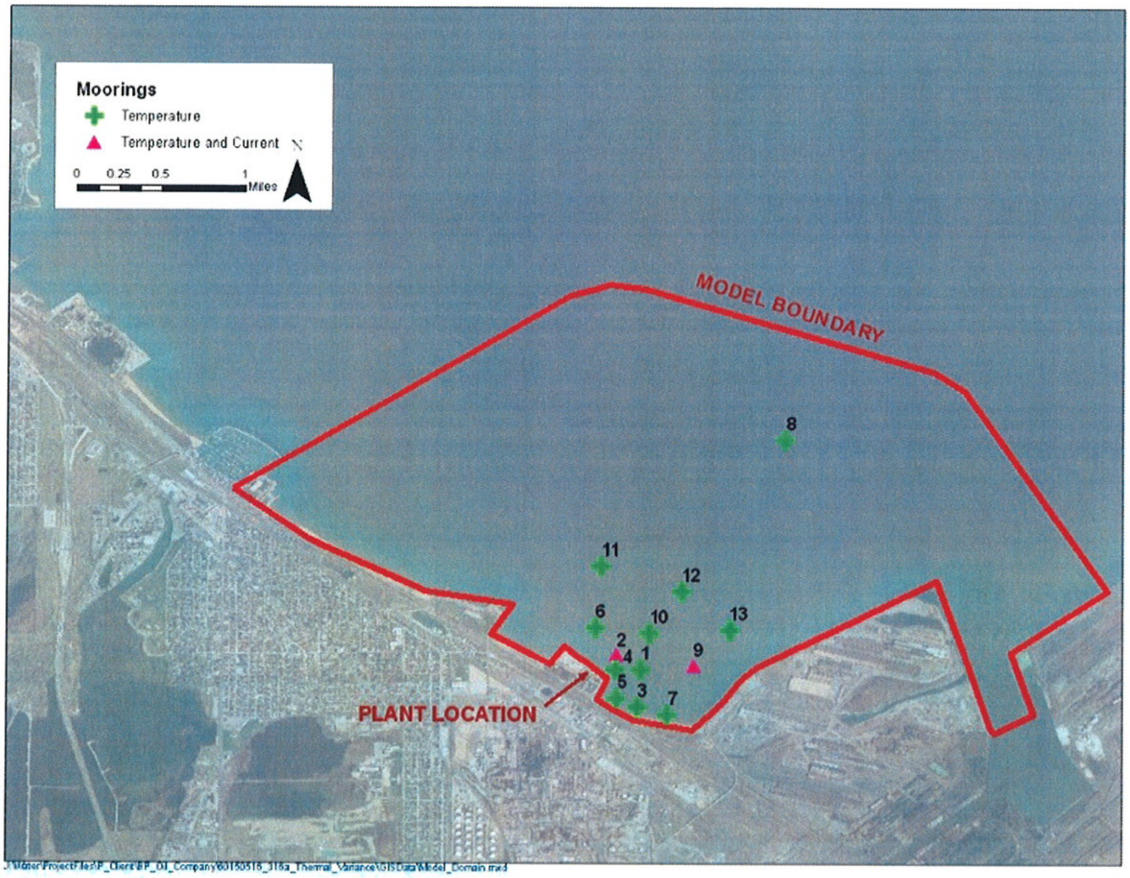


Figure 3-1. Model Domain

3.2.1 Model Grid

A finite-difference grid was developed to discretize the portion of Lake Michigan that is included in this model. Figure 3-2 demonstrates the curvilinear grid that composes the model domain. The full domain was divided into 1,265 cells. Model cells vary in size to provide a higher level of resolution in the area nearest the thermal plume and less resolution in the portions of the model domain farther afield from the discharge. Close to the thermal discharge cells are approximately 100 feet on a side (30 meters). At the open boundary on Lake Michigan the cells are approximately 1,300 feet on a side (400 meters). The model domain was further divided into six vertical layers of variable thickness, where each layer represents approximately 1/6 of the water depth at every cell location in the model domain.

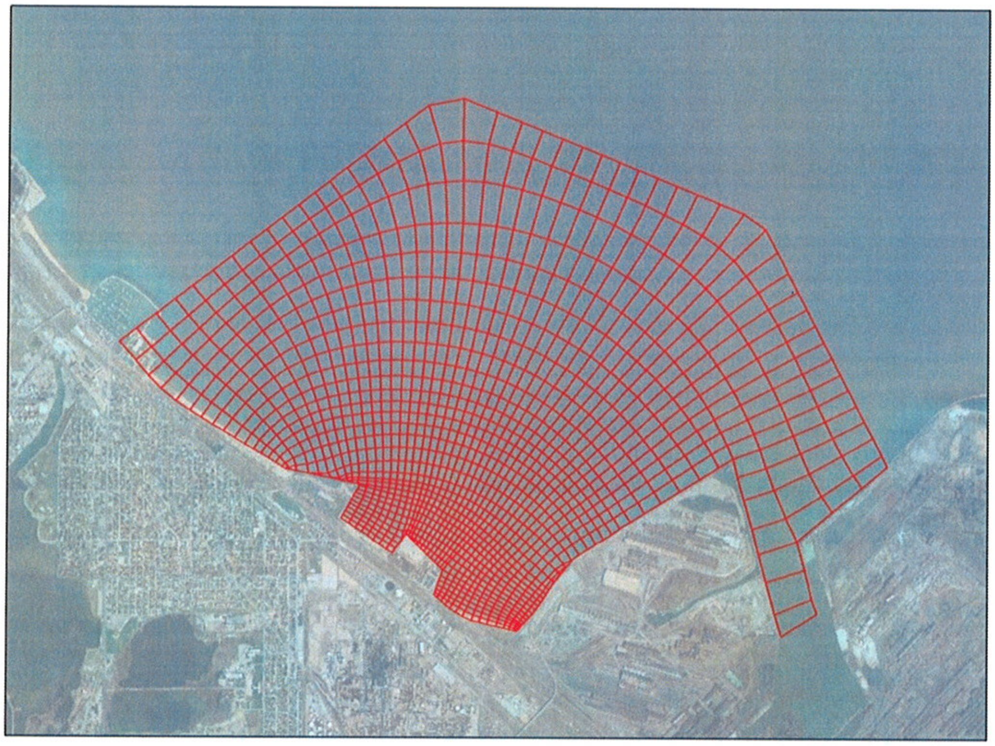


Figure 3-2. Model Grid

3.2.2 Model Bathymetry

Once the model grid was developed, the bathymetry data was interpolated to the model grid. The bathymetry is shown in Figure 3-3. Each model cell was assigned an average bottom elevation referenced to the International Great Lakes Datum 1985 (IGLD1985). National Oceanographic and Atmospheric Administration (NOAA) navigation charts were digitized and used to establish bathymetric elevations. The elevations were field-verified based on survey depths collected during the reconnaissance surveys. During the survey, it was noted that depths near the thermal discharge varied significantly as compared to the NOAA charts. The model bathymetry was adjusted to reflect these differences within 1,000 feet of the thermal discharge. Bathymetry data was collected at locations more than 1,000 feet from the thermal discharge, but the data collection density (distance between locations measured) was not sufficient to replace navigation chart soundings. Therefore, only the collected bathymetric data near the shoreline was used to correct data from NOAA navigation charts.

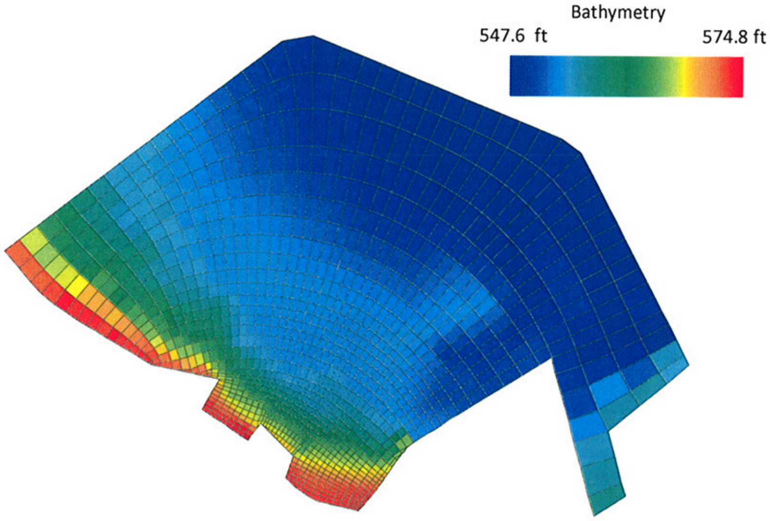


Figure 3-3. Model Bathymetry

3.2.3 Initial Conditions

Initial conditions were required at every cell in the model domain for water surface elevation, and at every cell and all depths for temperature. The choice of initial conditions can affect model predictions at the beginning of a model run. In running the model of the thermal discharge, a spin up period of seven days was used at all times in order to allow the effect of initial conditions to be eliminated from the calibration, validation, and scenarios.

The initial water surface was set to the average water surface elevation of Lake Michigan, 574.5 feet IGLD1985 (175.1 meters IGLD1985). Initial temperature conditions were established based on average ambient water temperatures at the beginning of the field period. After the seven day spin-up period the model converged. The model results from prior to convergence were not included in the model analysis.

3.3 Boundary Conditions

An accurate representation of boundary conditions is essential to produce accurate model predictions. Boundary conditions for flow and temperature were required at the discharge location over the time period of the model simulation. The plant discharge flow and temperature vary over time. Actual plant data (as described in Section 2.4.2) were used for the calibration and validation periods, while maximum operating flow (96.4 MGD current, 81.8 MGD future) and permitted thermal loading values (1.7 E+9 BTU/hr for both current and future) were used for the scenario predictions.

Boundary conditions in the form of atmospheric conditions (e.g., wind speed and direction, dry bulb air temperature, relative humidity, cloud cover, hours of daylight, solar radiation, etc.) were also specified and were entered as time-varying inputs to reflect the conditions measured locally. The atmospheric conditions were compiled from multiple sources. Wind speed and directions were assigned using the recorded wind data from the nearest NOAA NDBC buoy (Station ID CHII2) near Chicago, Illinois. All other weather data was collected from weather stations at Gary, Indiana (Station ID KGYY) and Whiting, Indiana (Station ID KINEASTC3). While the weather station at Whiting, Indiana did provide wind speed and direction data, the weather station is inland and wind speeds would have to be corrected for speeds over open water. For this reason, it was determined that the NOAA NDBC buoy would provide a more accurate representation of open water wind speeds within the model domain.

In this model an open boundary represents the influence of macro-scale hydrodynamic behavior of Lake Michigan. Boundary conditions for water level were assigned to the open boundary using the recorded water levels for the Calumet Harbor Buoy (Station ID 9087044). In addition to changes in water level, there are current patterns that form throughout Lake Michigan. The Great Lakes Coastal Forecasting System (GLCFS) (NOAA, 2010b) is a hydrodynamic model of all of the Great Lakes based on the Princeton Ocean Model and maintained by NOAA. The model predicts currents, water level, and temperature throughout Lake Michigan. The model resolution of the GLCFS model is not sufficient to characterize the thermal discharge plume at Whiting, Indiana, but the model does provide accurate descriptions of circulation patterns in Lake Michigan as a whole. The GLCFS model current predictions were used as boundary conditions. The northwest boundary represents the GLCFS model cell 21,6 which was used to dictate local currents generated by the hydrodynamics in Lake Michigan. The open boundary has two current boundaries, one to the northeast and one to the northwest of the thermal discharge. GLCFS model cell 21,6 represents the boundary to the northwest and in order to maintain mass balance within the model domain the northeast open boundary was inversely coupled to the northwest open boundary. In this way, the open boundary incorporates the overall behavior of Lake Michigan into the fine-scale model domain used to characterize the thermal plume.

All of the data sources used to drive the boundary conditions of the model are shown in Figure 3-4. Boundary Condition Data Sources which depicts the approximate boundary of the model (shown in red) and the various locations where boundary condition data was collected.

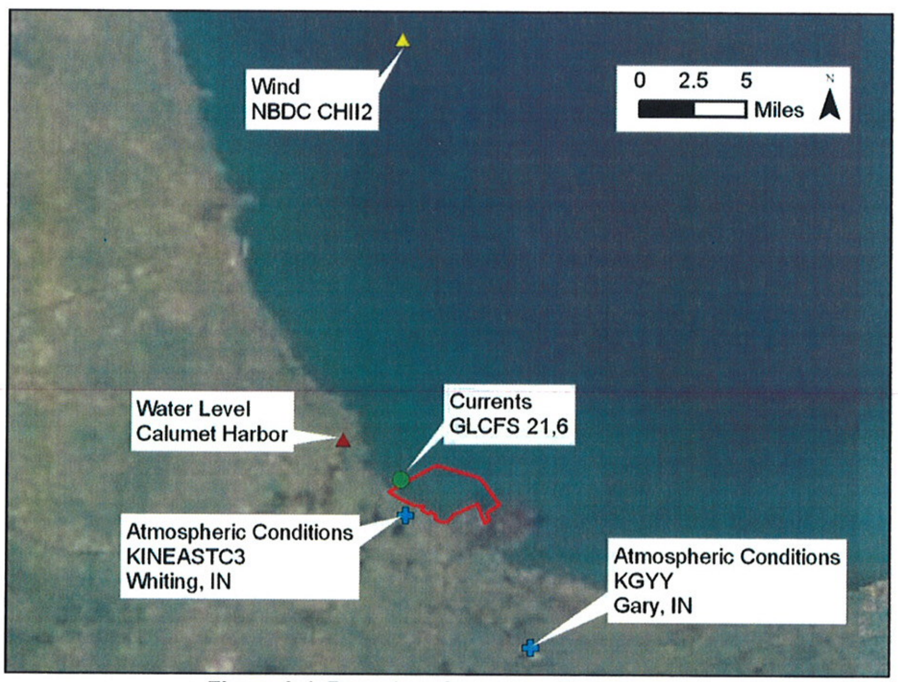


Figure 3-4. Boundary Conditions Data Sources

3.4 Model Calibration

Model calibration is the process of iteratively comparing model predictions with observed data followed by adjustment of input parameters to improve the "fit" of the model to the data. If a model is well calibrated, the predicted values are well matched to the observed values. If the predicted values are not well matched to the observations, model input parameters are adjusted to improve the predictions. The BP Whiting Refinery thermal discharge model was calibrated to two aspects of lake behavior. Specifically, the hydrodynamic parameters were adjusted to match predicted depth-averaged current magnitudes with observed depth-averaged current magnitudes at two mooring locations, and the thermal parameters were adjusted to match predicted depth-averaged water temperatures to observed depth-averaged water temperatures at five mooring locations.

After evaluation of initial model predictions, and comparison to calibration data, the calibration process entailed making minor adjustments to several model parameters, specifically:

- Adjustment of bottom roughness to calibrate current speeds
- Adjustment of solar radiation attenuation, evaporative heat transfer, and convective heat transfer to calibrate thermal model predictions

Each of these parameters contributes to the transfer of heat energy within the lake and between the lake and the atmosphere. The parameters were adjusted such that predicted water temperatures at five mooring locations matched the observed temperatures at those same locations. The parameters were adjusted within reasonable ranges based on professional judgment and literature as summarized in Ji (2008).

The model was calibrated to a 14-day period from September 27, 2010 to October 11, 2010. Model calibration progressed in two-steps. First, the hydrodynamics were calibrated against the ADCP data. Second, the thermal data was calibrated against the results for several thermistor array mooring locations.

Three statistics were used to evaluate the level of matching between the observed data (from field data collection) and the predicted data (from model results). The first statistic is the residual which is defined in Equation 3-1:

Equation 3-1. Calculation of Residual

$$\text{Residual} = x_i - y_i$$

Where: x_i = observed data value
y_i = predicted data value

The second statistic that was used to evaluate the level of matching between observed data and predicted data is the standard deviation of residuals which is defined in Equation 3-2:

3-2 Calculation of Standard Deviation of Residuals

$$Standard\ Deviation = \sqrt{\frac{\sum(r_i - \bar{r})^2}{n}}$$

Where: r_i = residual value
r bar = mean residual value
n = number of observed and predicted data pairs

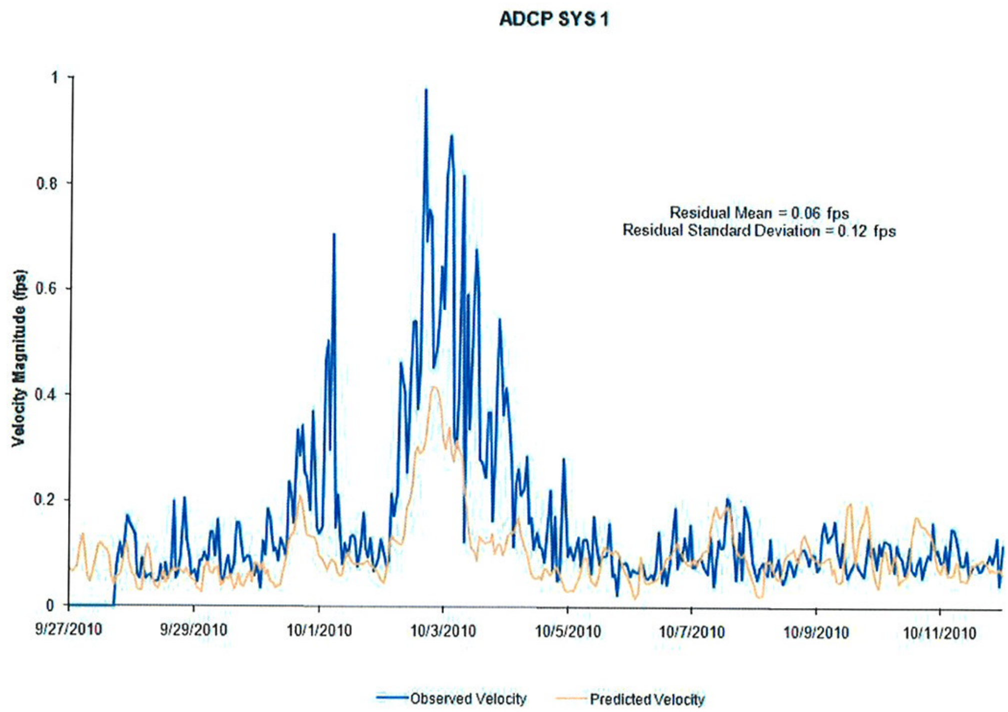
The average residual value and the standard deviation of all residual values were used to evaluate model bias and model stability. The third statistic used to evaluate the level of matching between observed data and predicted data is the square of the Pearson product moment correlation coefficient (R^2) of a linear regression applied to a comparison of predicted to observed data. The R^2 is defined mathematically in Equation 3-3. R^2 is a measure of how well the predicted data match the observed data in time. An R^2 value equal to 1 is a perfect match.

Equation 3-3. Calculation of Square of Pearson Correlation Coefficient

$$R^2 = \left(\frac{\sum\ (x_i - \bar{x})(y_i - \bar{y})}{\sum\ (x_i - \bar{x})^2 \sum\ (y_i - \bar{y})^2}\right)^2$$

Where: R^2 = square of Pearson product moment correlation coefficient
x_i = observed data value
y_i = predicted data value
$\bar{x}$ = mean of observed data
$\bar{y}$ = mean of predicted data

The hydrodynamic calibration results from the two ADCP mooring locations are shown in Figure 3-5. The model domain is a large open water area with complex hydrodynamics. Therefore the most useful way to present the comparison between observed currents and predicted currents is through the presentation of depth-averaged current speeds. Figure 3-5 shows generally good agreement between observed current speeds and predicted current speeds. The only notable variation between the two data sets occurs on and around October 3. The observed data shows elevated, but highly variable current speeds. This is most likely caused by waves generated by winds blowing along the full reach of Lake Michigan. Substantial wave activity was recorded at the NOAA NDBC Buoy east of Milwaukee (Station ID 45007) in the same time period. The EFDC model does not incorporate wave action into the model domain. Sustained convective transport of thermal discharge water will not be significantly influenced by intermittent wave action. The dominant forces in the movement of the thermal plume will be hydrodynamic circulation patterns and local effects due to the discharge itself.



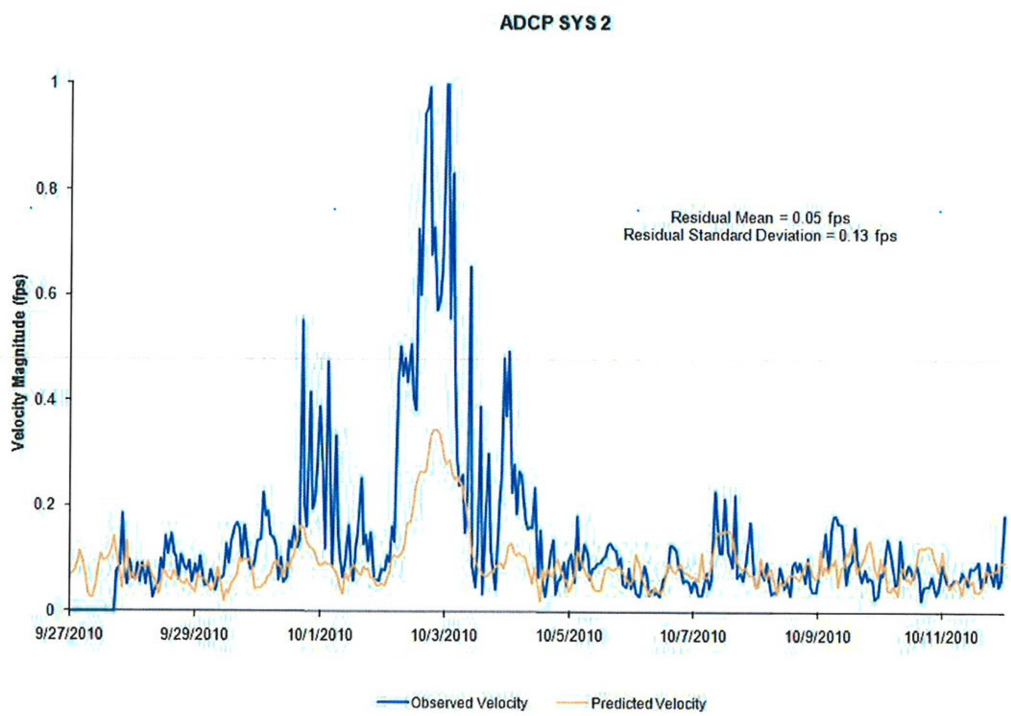


Figure 3-5. Calibration Period: Depth-Averaged Currents Observed and Predicted Data

The hydrodynamic calibration results were used to insure that current speeds generated by circulation patterns and atmospheric conditions were appropriate. The current directions were checked and calibration parameters were adjusted to provide a visual best fit of the general hydrodynamic behavior. The purpose of the modeling effort is to predict thermal behavior in the model domain. Hydrodynamic behavior controls the movement of the thermal plume. The calibration of thermal parameters also provides an opportunity to check hydrodynamic behavior because the hydrodynamic behavior must be modeled well to show good agreement in the thermal calibration results. Therefore, a rigorous numerical evaluation was reserved for the investigation of the thermal calibration results.

All data collected during the field program were considered in comparison to model results, but moorings TM02, TM09, TM11, TM13, and TM06 were chosen for quantitative comparison to model results in order to ensure good agreement with observed data across the full model domain. Moorings TM03, TM05, and TM07 were nearshore moorings that were used to investigate whether the model was capturing observed temperatures, but because these moorings are within the zone of discharge induced mixing, the turbulent conditions at these moorings preclude them from being a part of the quantitative comparison of observed and predicted data. The thermal model calibration results from the five mooring locations are shown in Figure 3-6. The figure shows the depth-averaged time series of modeled and observed water temperatures at mooring TM02, TM09, TM11, TM13, and TM06. The time series of observed and predicted temperatures are presented as depth-averaged values for the calibration period because the five moorings showed well mixed conditions in both the observed and predicted data.

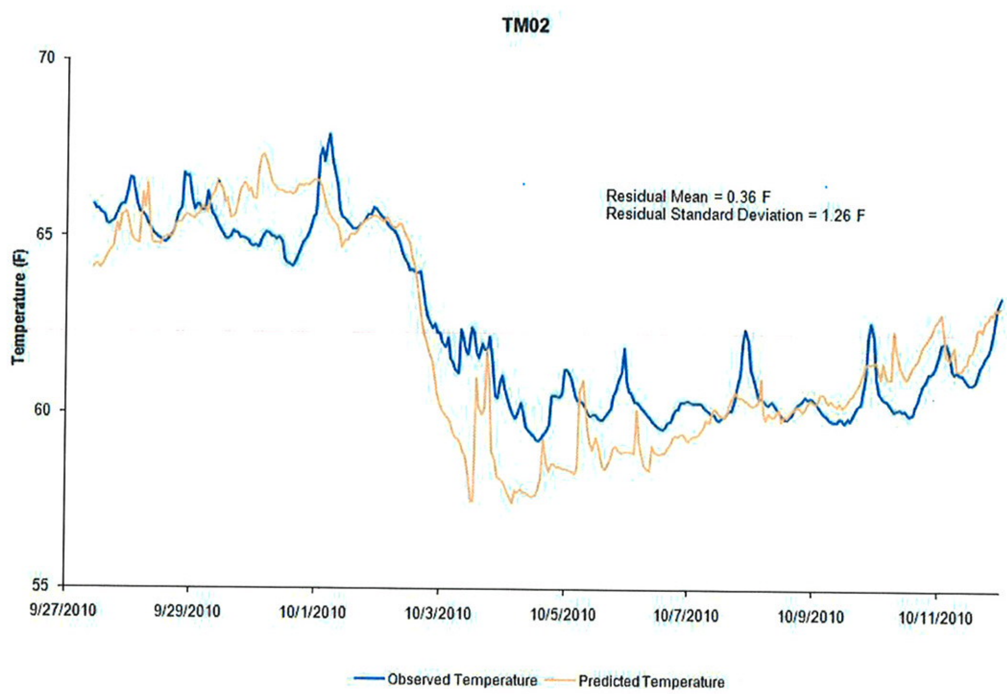
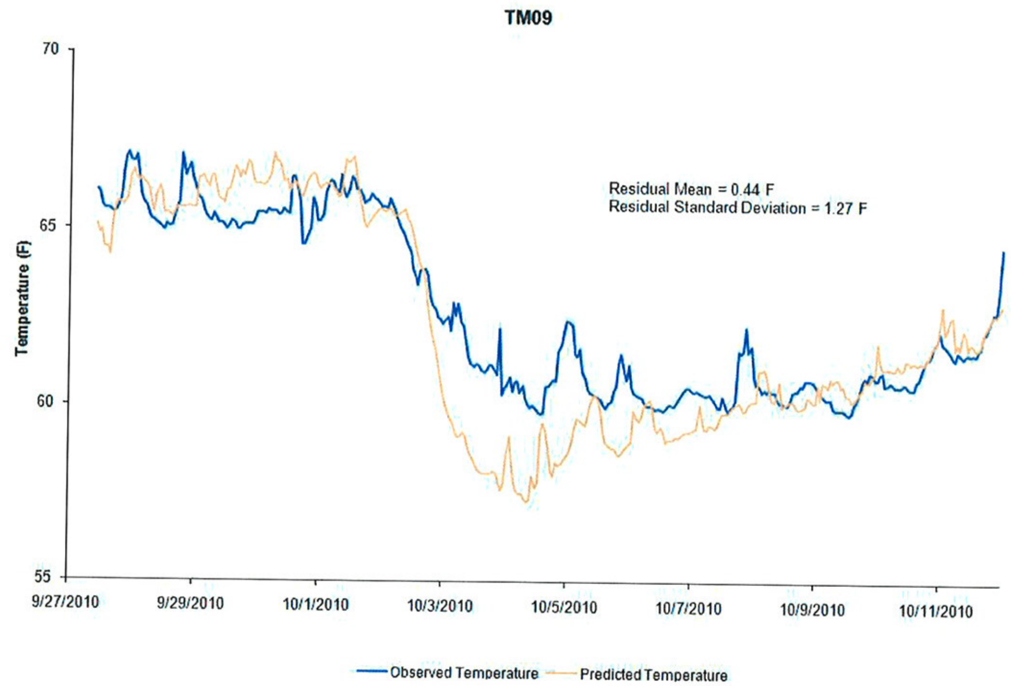


Figure 3-6a. Calibration Period: Depth-Averaged Temperature Observed and Predicted Data



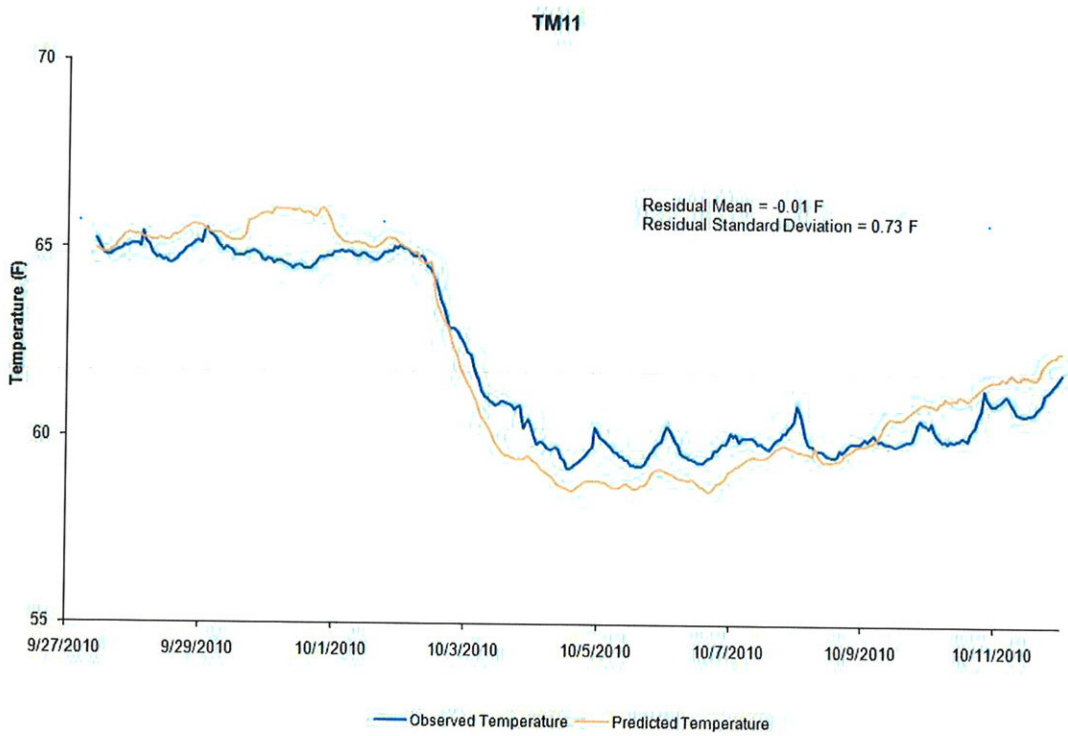
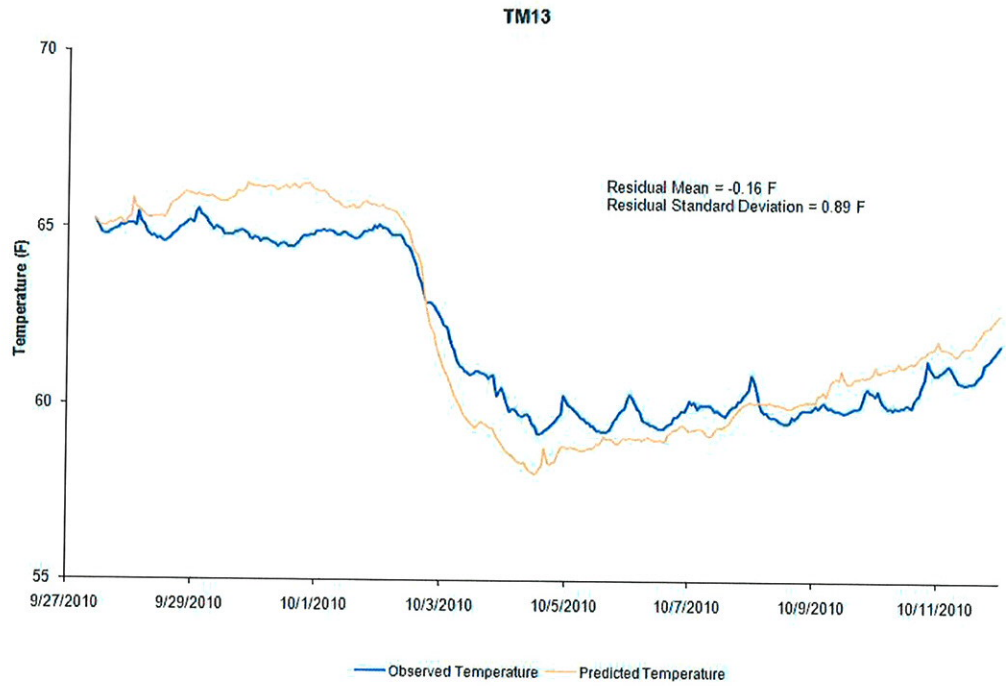


Figure 3-6b. Calibration Period: Depth-Averaged Temperature Observed and Predicted Data



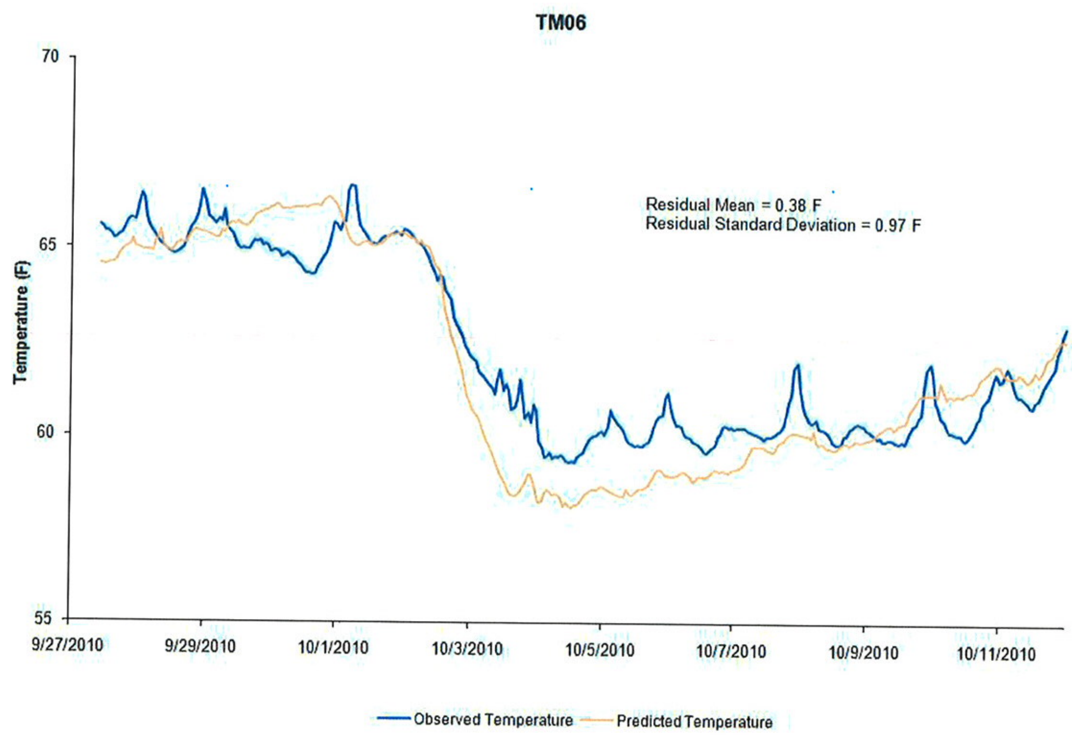


Figure 3-6c. Calibration Period: Depth-Averaged Temperature Observed and Predicted Data

The depth-averaged model predictions at each mooring location match well to the observed data at the same locations. The model does over predict the drop in water temperature that occurs throughout the entire domain between October 2, 2010 and October 4, 2010. The model, however, does recover the excessive drop in water temperature by October 7, 2010. The source of the dramatic variation was found to be the open boundary that utilizes data from the GLCFS model of Lake Michigan.

The behavior of the boundary conditions of the model have a significant impact on the degree of matching between observed and predicted data. The predicted temperature from the GLCFS model of Lake Michigan is a boundary condition in the EFDC model of the BP Whiting Refinery discharge. The GLCFS temperature is used in the EFDC model as the temperature of flow that enters the model domain through the open boundaries of the EFDC model. The predictive capacity of the EFDC model is coupled to the predictive capacity of the GLCFS model because of this boundary condition.

Figure 3-7 shows the observed temperature at mooring TM08 and the GLCFS temperature used as the ambient water temperature boundary condition. Mooring TM08 was located well out into the open water of Lake Michigan and can be appropriately compared to the temperature results from the GLCFS model. Figure 3-7 clearly demonstrates that the relationship between observed temperatures in open water and the GLCFS model predictions are variable during the calibration and validation periods. The over prediction of the drop in temperature seen on and around October 3, 2010 can be seen in Figure 3-7. Additionally, a consistent difference between observed data and the GLCFS prediction can be seen throughout the validation period.

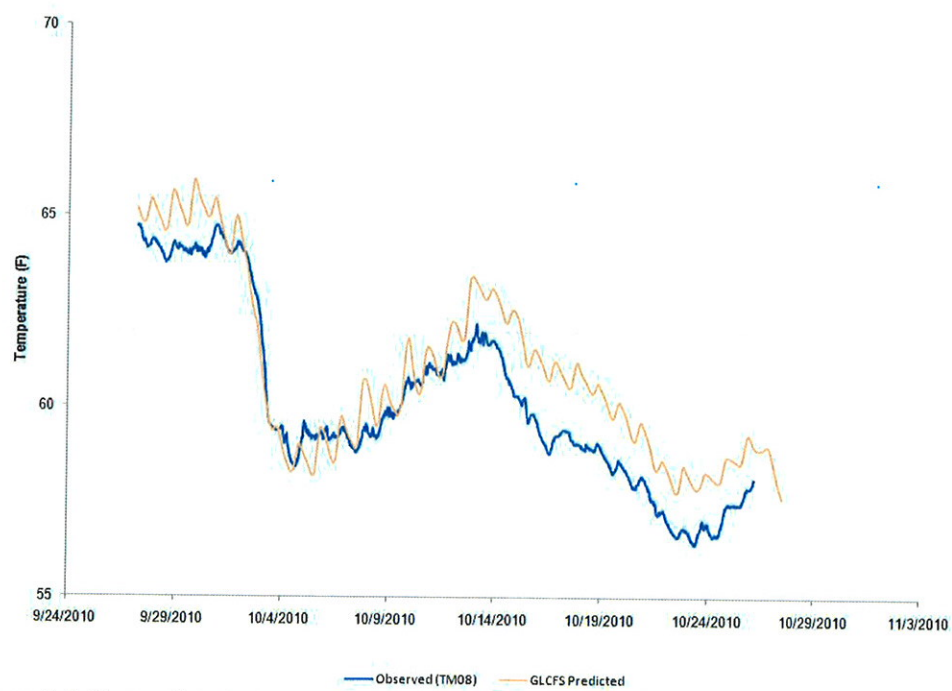


Figure 3-7. Comparison between GLCFS Model Predictions and Observed Data at Mooring TM08

The GLCFS model has been calibrated and validated and is maintained by NOAA. The model predicts temperatures throughout Lake Michigan with good accuracy, but the resolution of the model is limited by the size of the grid cells which are approximately 1.25 miles (2 kilometers) in size, therefore temperature variations of approximately one degree Fahrenheit in a single grid cell represent a small fluctuation in the overall GLCFS model predictive capacity. Similarly, a deviation over a period of two weeks is small relative to the time period that the GLCFS model covers. The BP Whiting Refinery thermal discharge model has much higher resolution than the GLCFS model and is more sensitive to local temperature changes. The BP Whiting Refinery thermal discharge model is coupled to the GLCFS model through the assignment of boundary conditions. While this may create short term variations between observed and predicted data, it also allows for the model to be applied over a large range of current, historical, and potentially future conditions. The bias generated from the GLCFS model oscillates between positive and negative values during the field period. It was concluded that the long term bias is not significant and the benefits of having the EFDC model coupled to the GLCFS model were significant. Therefore, it is appropriate to couple the EFDC model to the GLCFS model.

Figure 3-8 presents the correlation between the predicted and observed data for the five moorings. The hourly model predictions and temperature measurements are well correlated, with an R^2 ranging from 0.82 to 0.95. Table 3-1 summarizes the calibration statistics of five mooring locations.

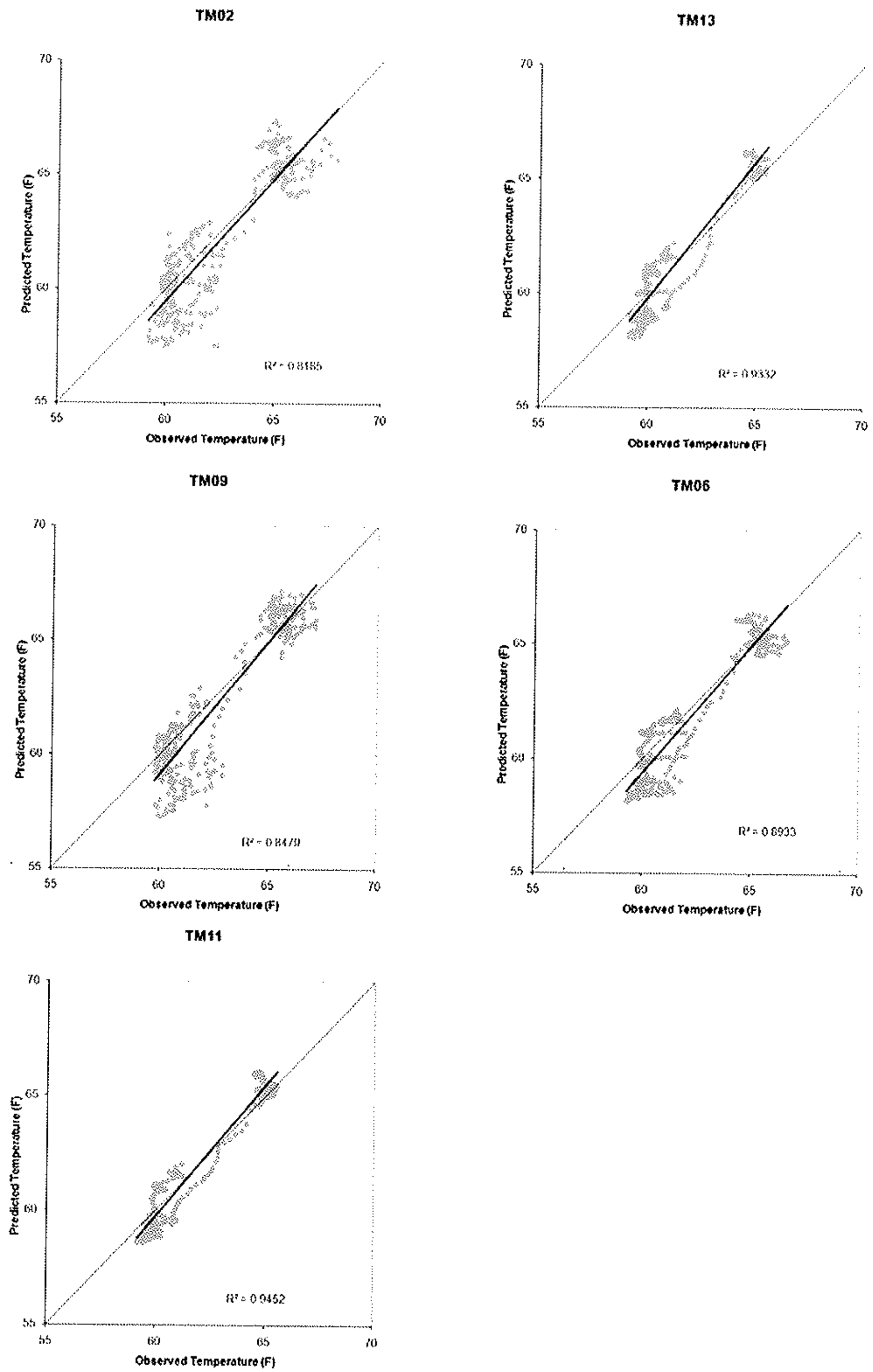
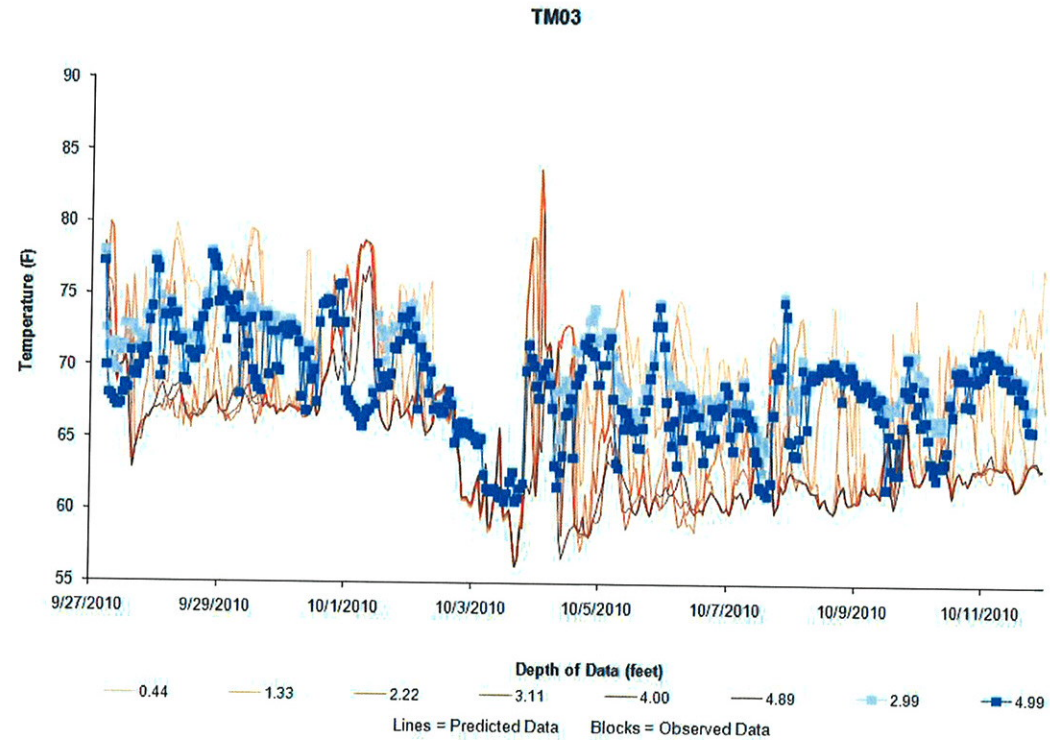


Figure 3-8. Calibration Period: Depth-Averaged Temperature Observed Data vs. Predicted Data

Table 3-1. Summary of Calibration Period Comparison

Mooring	Residual Average (F)	Residual Standard Deviation (F)	R^2
TM02	0.36	1.26	0.8185
TM09	0.44	1.27	0.8479
TM11	-0.01	0.73	0.9452
TM13	-0.16	0.89	0.9332
TM06	0.38	0.97	0.8933
Average	**0.20**	**1.02**	**0.8876**

In addition to depth-averaged calibration results at these five mooring locations, Figure 3-9 shows a comparison of observed data and predicted data at moorings TM03, TM05, and TM07. These moorings are all in closer proximity to the thermal discharge. These moorings are within the zone of discharge induced mixing, the turbulent conditions at these moorings preclude them from being a part of the quantitative comparison of observed and predicted data. Depth averaging is not appropriate in this portion of the model domain because a significant vertical thermal profile may exist. Additionally, during the field program, wave heights of two feet were reported in this area of the model domain. The EFDC model does incorporate wave action, but this wave action may create turbulent conditions that are not captured within the model. The graphs shown in Figure 3-9 are presented only to demonstrate that the peak temperatures seen in the observed data are captured by the EFDC model.



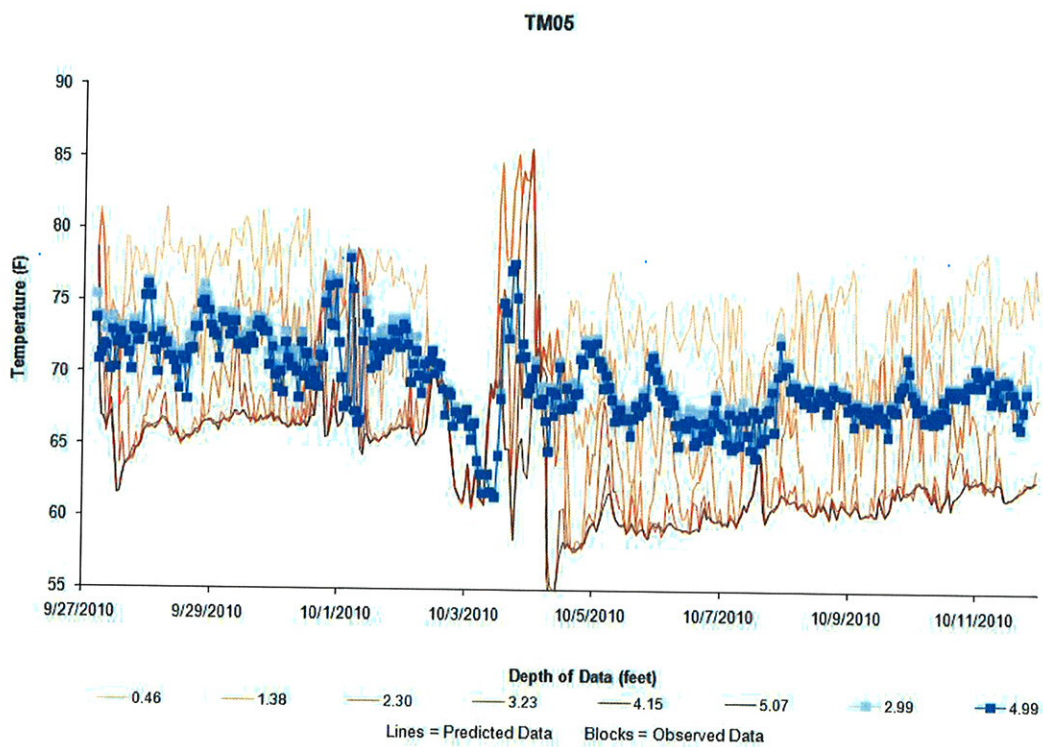


Figure 3-9a. Calibration Period: Observed Data and Predicted Data All Depths

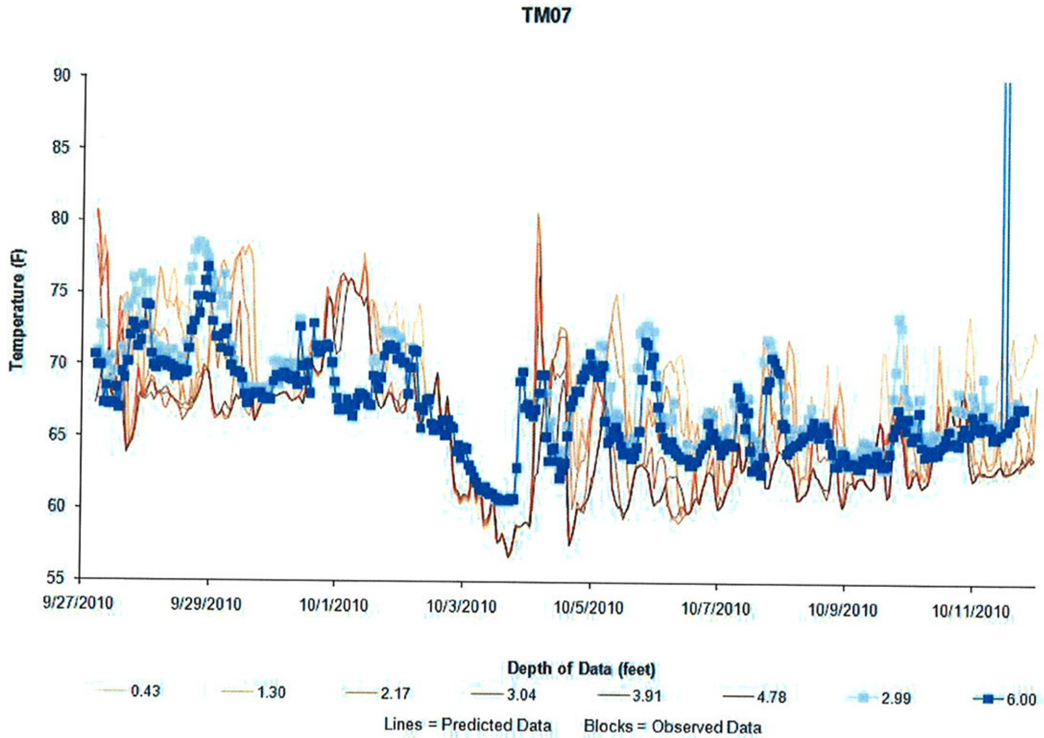


Figure 3-9b. Calibration Period: Observed Data and Predicted Data All Depths

Based on these results, the calibrated model does not demonstrate a significant bias and the variability of the data is within an acceptable range. There is no generally accepted minimum value for the level of matching between observed and predicted data, but the USEPA provides some technical guidance for calibration of basic guidance values for acceptable calibration of water quality models in estuaries. The specific model application for the BP Whiting Refinery discharge is different (i.e. a Lake as opposed to an estuary), but the same statistics apply to this application. The USEPA (1990) suggests threshold values of ±45% for relative error and a correlation coefficient of 0.60 for water quality studies. The relative error for the calibration period was 0.3% and the correlation coefficient was 0.94. These statistics demonstrate strong matching between modeled and observed data. There is no significant bias, and the investigation of temperatures near the discharge show that the model is capturing peak water temperatures near the outfall. Therefore, the model was considered to be well calibrated.

3.5 Model Validation

Following completion of the model calibration, the model was validated to a separate set of data, measured outside of the calibration period. The validation period was from October 11, 2010 to October 25, 2010. The data used for the model validation period were depth-averaged water temperatures from moorings TM02, TM09, TM11, TM13, and TM06. Model validation results from the five mooring locations are shown in Figure 3-10. The model again captures well the general pattern of temperature change over the validation period. There is less variability in the observed data and accordingly, the model data is less variable as well. Figure 3-11 presents the correlation between the predicted and observed data for the five moorings during the validation period.

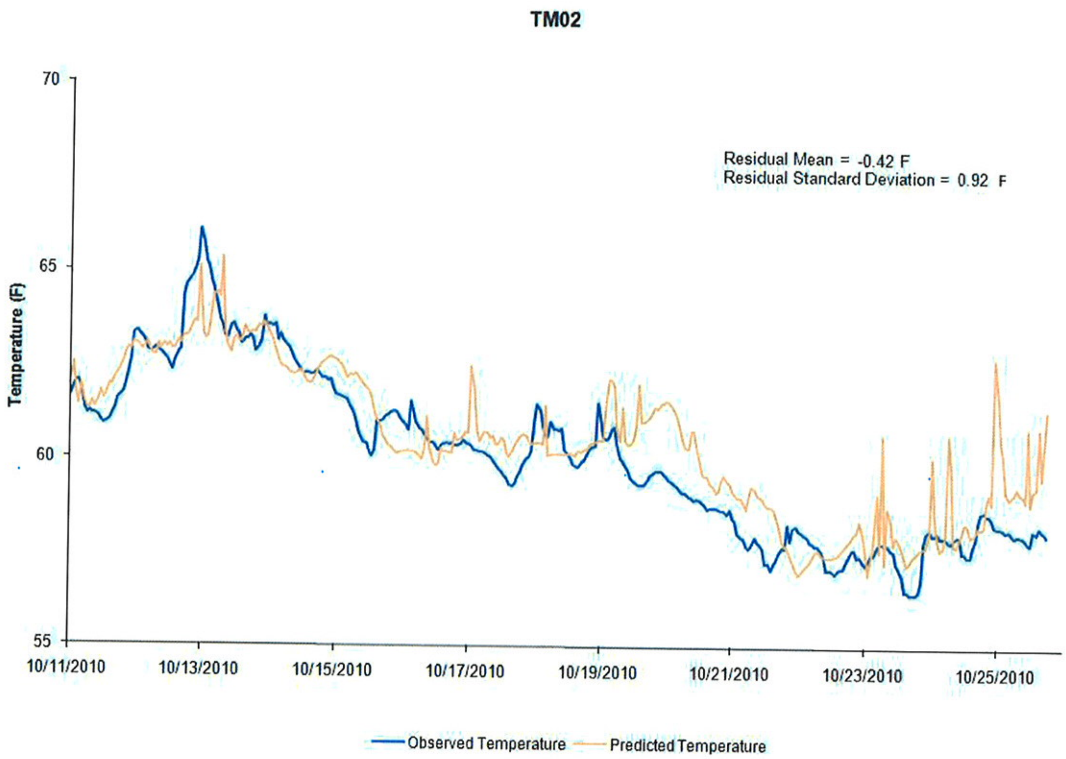
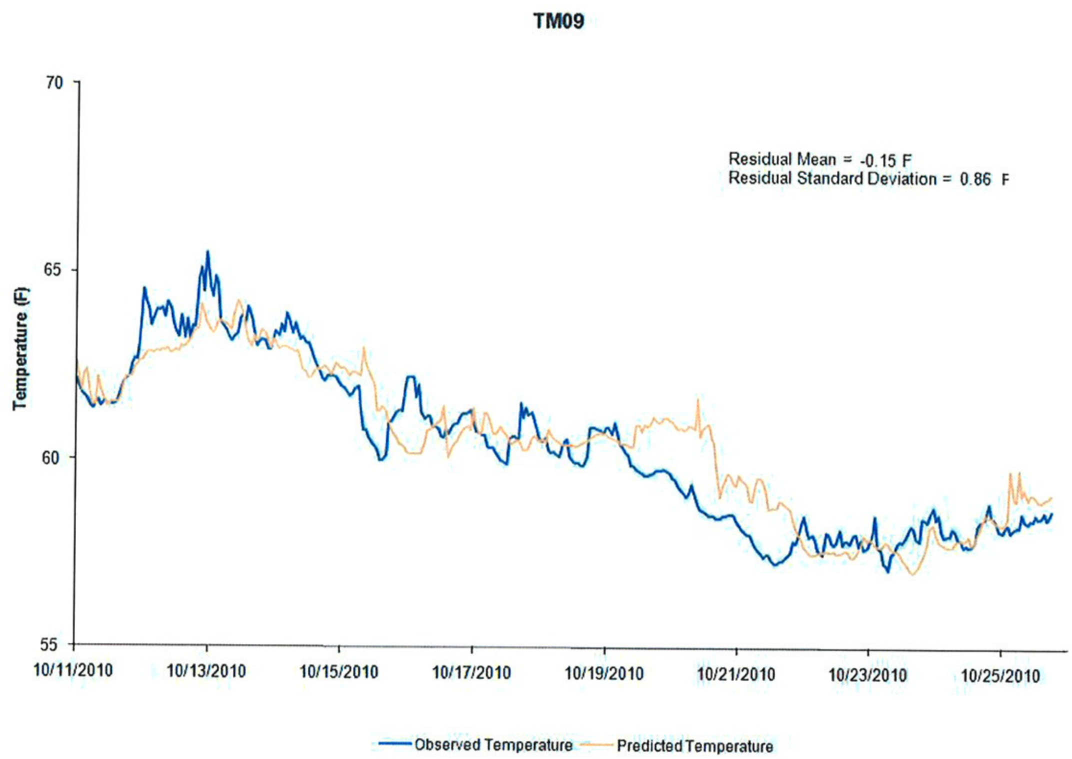


Figure 3-10a. Validation Period: Depth Temperature Observed and Predicted Data



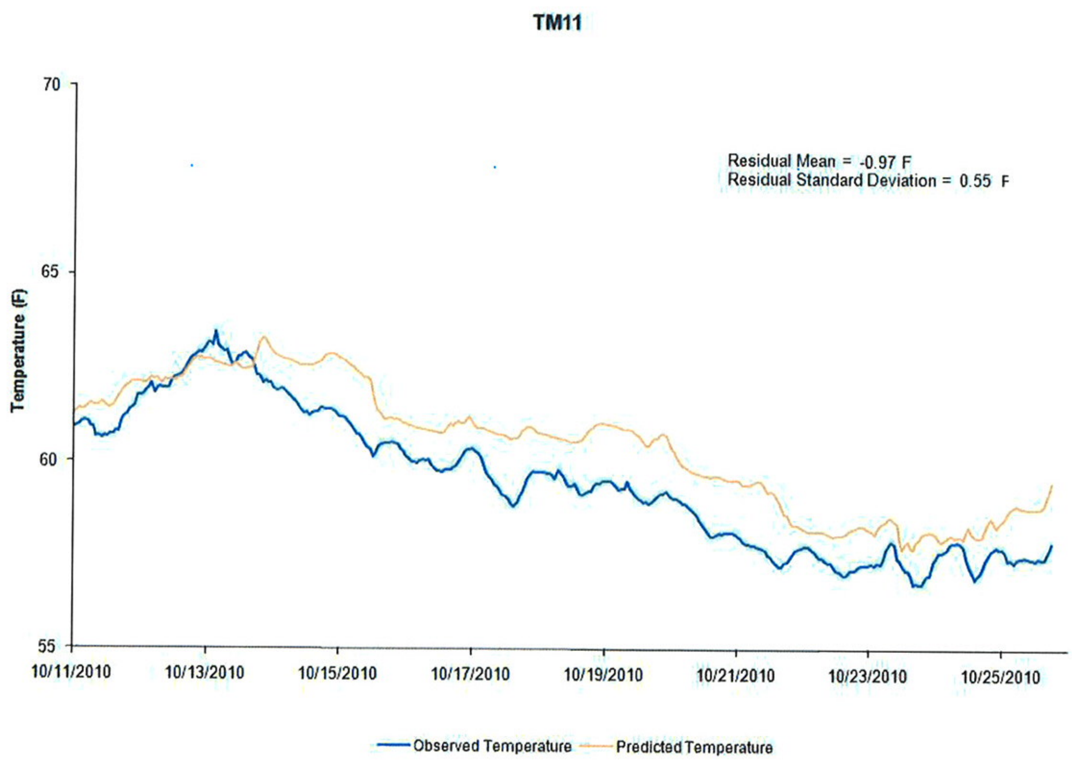
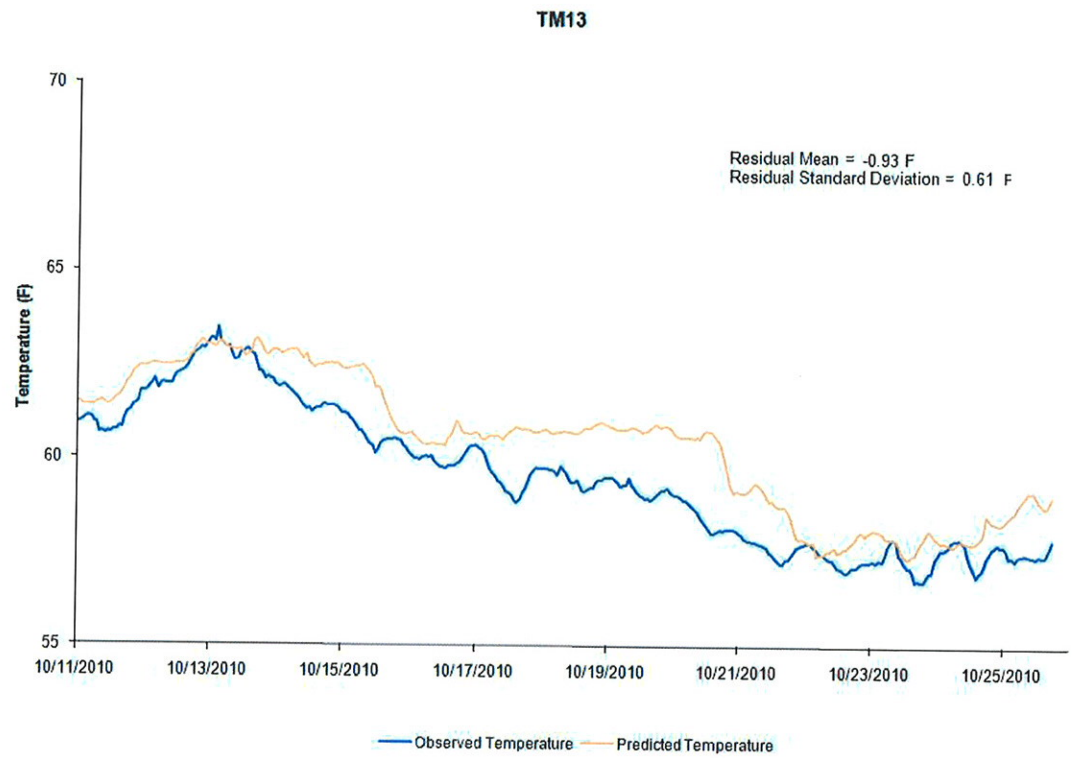


Figure 3-10b. Validation Period: Depth Temperature Observed and Predicted Data



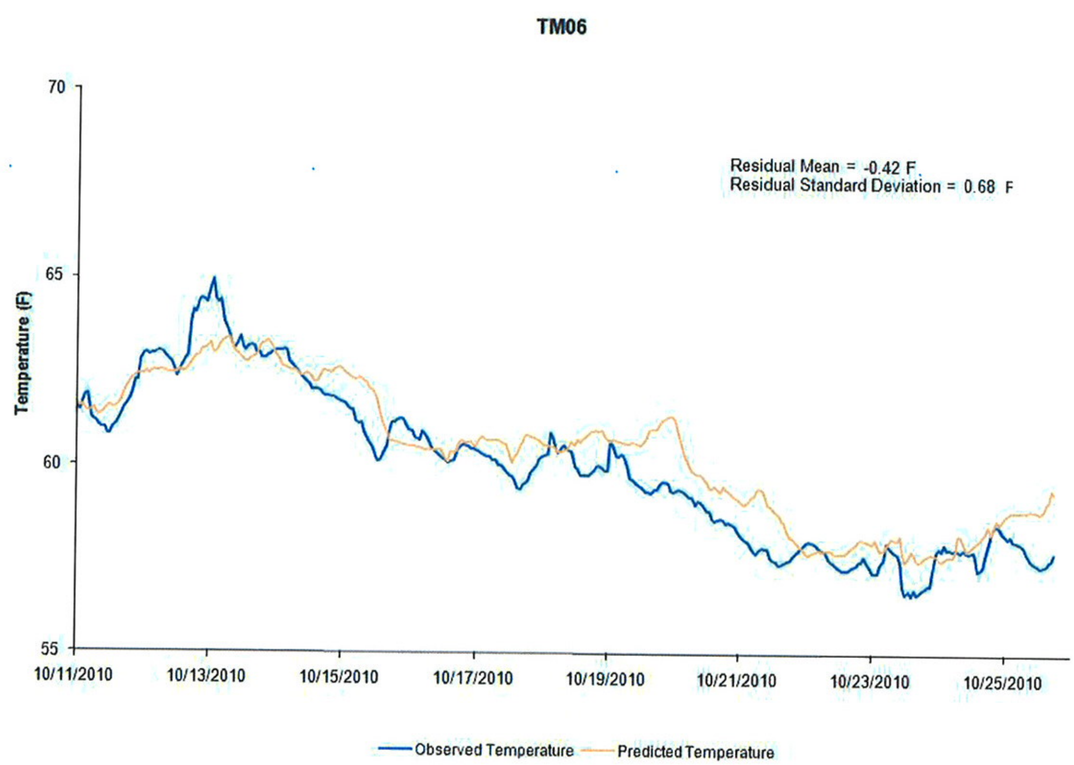


Figure 3-10c. Validation Period: Depth Temperature Observed and Predicted Data

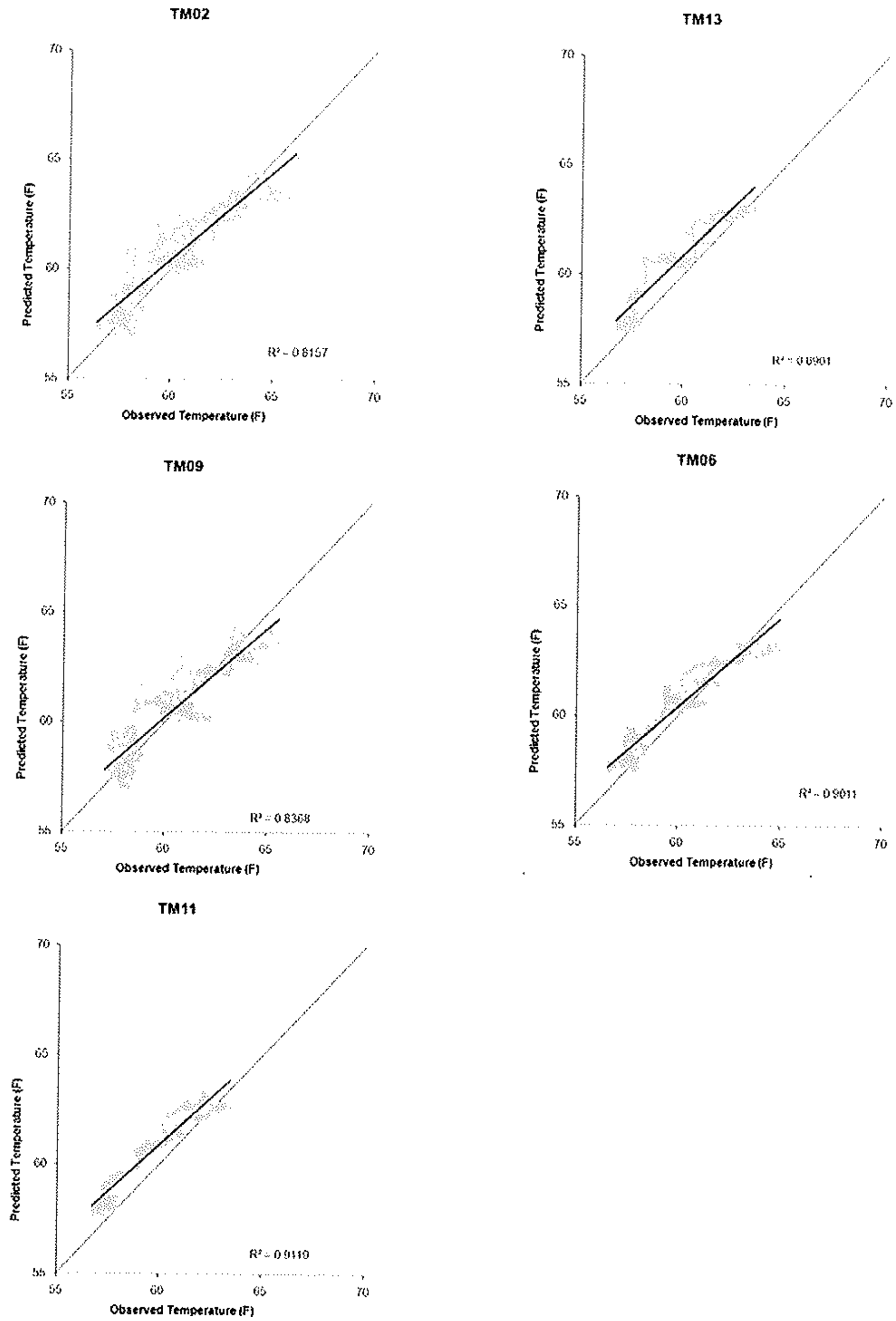


Figure 3-11. Validation Period: Depth-Averaged Temperature Observed vs. Predicted Data

Table 3-2 provides an overview of the statistics for the five mooring locations during the validation period. The hourly model predictions and observed temperature data remain well correlated, with an R^2 ranging from 0.81 to 0.91.

Table 3-2. Summary of Validation Period Comparison

Mooring	Residual Average (F)	Residual Standard Deviation (F)	R^2
TM02	-0.42	0.92	0.8157
TM09	-0.15	0.86	0.8368
TM11	-0.97	0.55	0.9119
TM13	-0.93	0.61	0.8901
TM06	-0.42	0.68	0.9011
Average	**-0.58**	**0.72**	**0.8711**

Figure 3-12 shows a comparison of observed data and predicted data at the moorings close to the discharge: TM03, TM05, and TM07. Again the graphs shown in Figure 3-12 are presented only to demonstrate that the peak temperatures seen in the observed data are captured by the EFDC model.

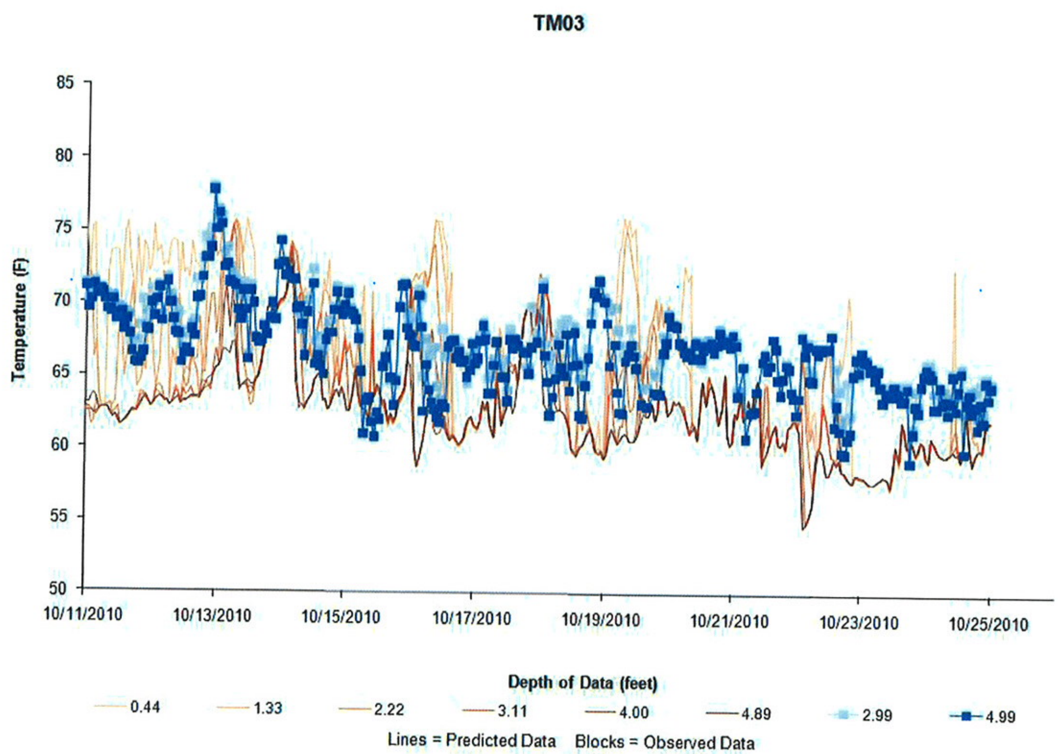
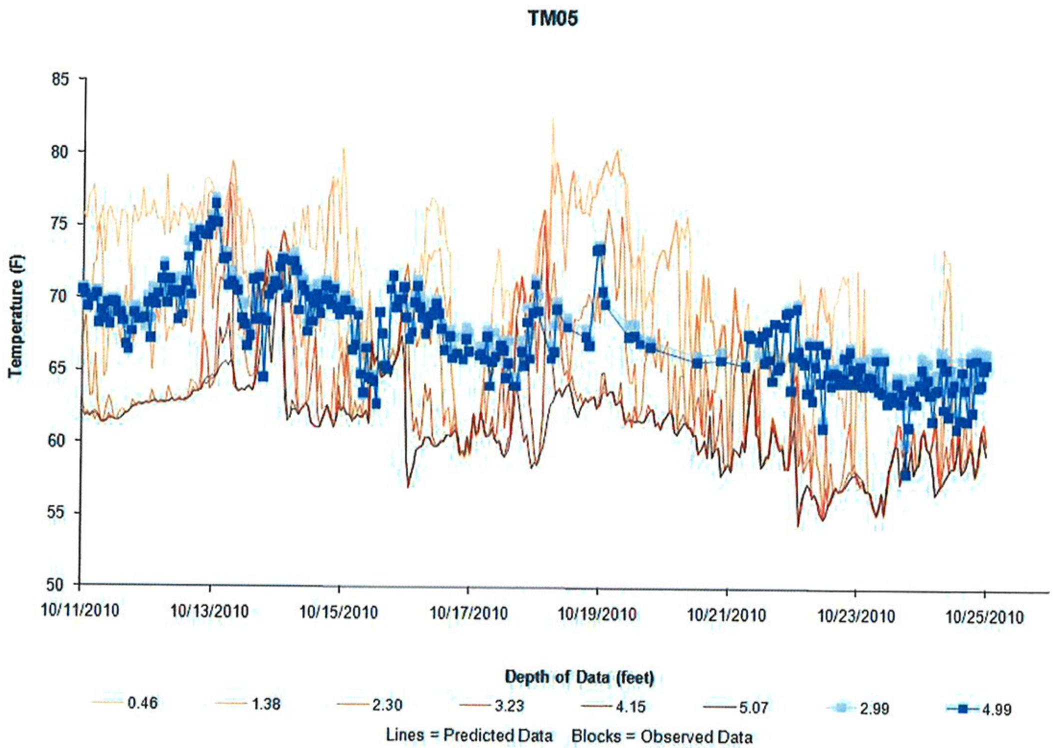


Figure 3-12a. Validated Period: Observed Data and Predicted Data All Depths



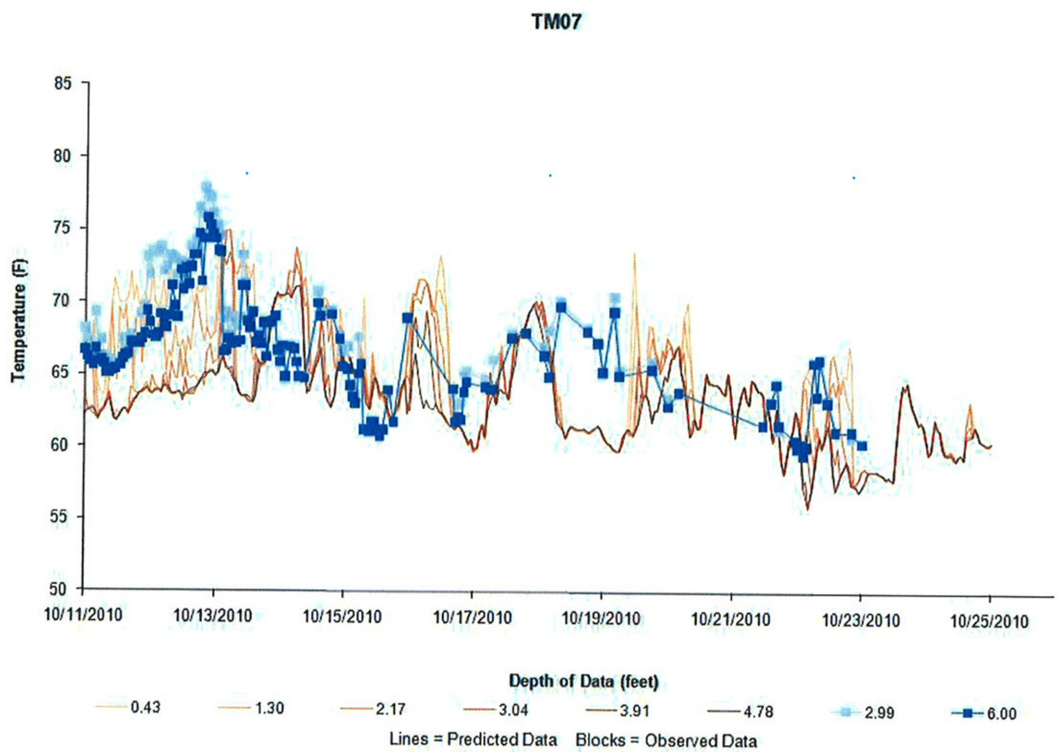


Figure 3-12b. Validated Period: Observed Data and Predicted Data All Depths

The model bias (average residual) shifts 0.78 F between the calibration period and the validation period. The source of this shift is the relationship between actual open water temperatures and the predictions of open water temperatures from the GLCFS model. The coupling of the EFDC model to the GLCFS model is discussed in detail in Section 3.4. Because of the importance of the GLCFS model predictions, it is helpful to evaluate the cumulative data set for the both the calibration period and the validation period. The cumulative data set created by the combination of the calibration and validation period yields a model bias of -0.20 F, which is minimal. On balance, the model slightly over predicts water temperatures, therefore the model can be considered to be conservative. The standard deviation for the cumulative data set is 1.02 F. The cumulative data set has a correlation coefficient of 0.9177 and a relative error of -0.33%. The correlation coefficient and relative error of the cumulative data set are well within acceptable limits as suggested by the USEPA (1990).

In general, the comparison of predicted data and observed data from the validation period indicates that the model calibration was acceptable and that the model is suitable for predictions outside of the calibration period and for predictions at multiple locations within the model domain. Given the complexity of modeling a thermal discharge in a small portion of such a large lake, the model calibration was deemed not only sufficient to meet the objectives of the study, but the best calibration achievable over the temporal and spatial range included in the calibration.

4.0 Model Application

The calibrated and validated model was used to predict the extent of the thermal plume under a range of simulated scenarios. Per IDEM's direction, the anticipated worst case scenarios were modeled to predict the maximum likely extent of the thermal plume. These worst case scenarios are not representative of normal operating conditions at the BP Whiting Refinery.

The anticipated worst case scenarios are a statistically warm summertime when warmer ambient temperatures reduce the availability of cooler water for mixing, and a springtime condition where warm air temperatures and cool water temperatures restrict heat loss through evaporation. The two seasonal variations were evaluated under both north-northwest and south-southeast ambient water current conditions. Finally, each of these scenarios was evaluated for the existing configuration of the BP Whiting plant and for the proposed future conditions. The results of this predictive modeling delineate the thermal plume.

4.1 Definition of Simulated Scenarios

The extent of the thermal plume is determined by a number of factors. The dominant factors are plant operation, ambient meteorological conditions, and ambient water current conditions. In order to predict the maximum likely extent of the thermal plume for these dominant factors, maximum plant operation conditions were considered to be the maximum monthly average plant discharge rates (96.4 mgd existing conditions, 81.76 mgd proposed conditions) and the maximum monthly average thermal loading to receiving water body (1.7E+09 BTU/hr for both existing and proposed conditions).

Meteorological conditions were selected to simulate conditions that inhibit heat dissipation through mixing and evaporation. Heat dissipation through mixing will be limited during warm weather conditions where the receiving water body does not provide cool waters to mix with the discharge water. To simulate an extreme case for this condition, a combination of meteorological conditions (wind, air pressure, humidity) that result in warm air temperature that had a probability of recurrence less than 5% was selected. For summer-time conditions, this analysis was conducted for a data set that includes all of the days in June, July, and August between 2005 and 2009.

Heat dissipation through evaporative heat transport will be limited when ambient water temperatures are consistently below ambient air temperatures. This condition most typically occurs in the spring. An extreme difference between air and water temperatures will result in rapid warming of ambient waters and the limitation of evaporation will be reduced. Therefore, a combination of meteorological conditions (wind, air pressure, humidity) that result in a 50% probability of recurrence was selected in order to avoid rapid warming of the ambient water, and maintain a stable limit on evaporation, thus creating a worst case. For spring-time conditions, this analysis was conducted for a data set that includes all of the days in March, April, and May between 2006 and 2009.

Figure 4-1 shows the daily average air temperature recurrence plot for the summer-time conditions and the difference between daily average air temperatures and daily average water temperatures for spring-time conditions. Based on this statistical analysis, August 2, 2007 was selected as the representative summertime day and April 16, 2008 was selected as the representative springtime day. The extreme case for ambient current speeds was considered to be depth-averaged ambient water current speeds, from the GLCFS model grid cell 21,6, that had a probability of recurrence of less than 5%. Figure 4-2 shows the probability of recurrence plots for both a dominant southeast to northwest current direction and a dominant northwest to southeast current direction.

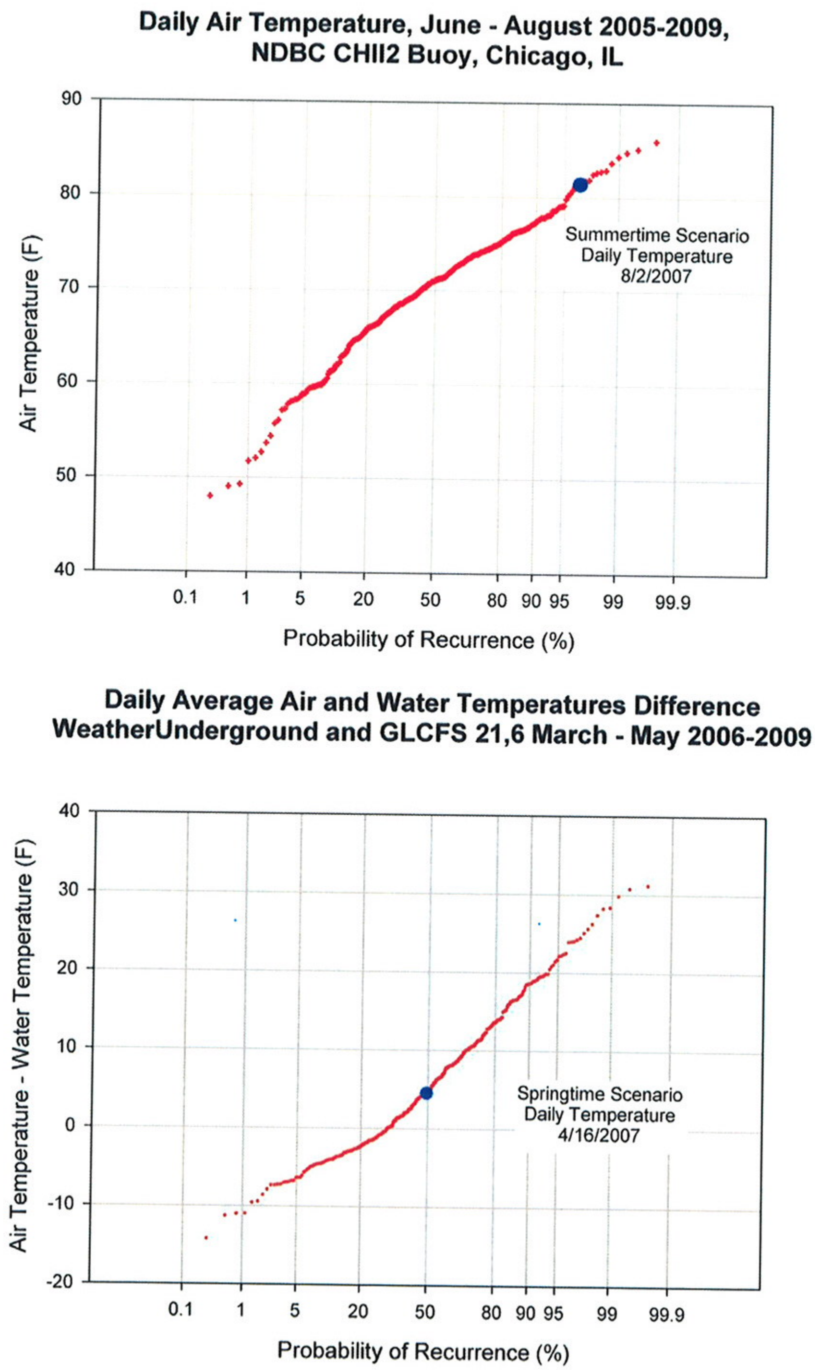
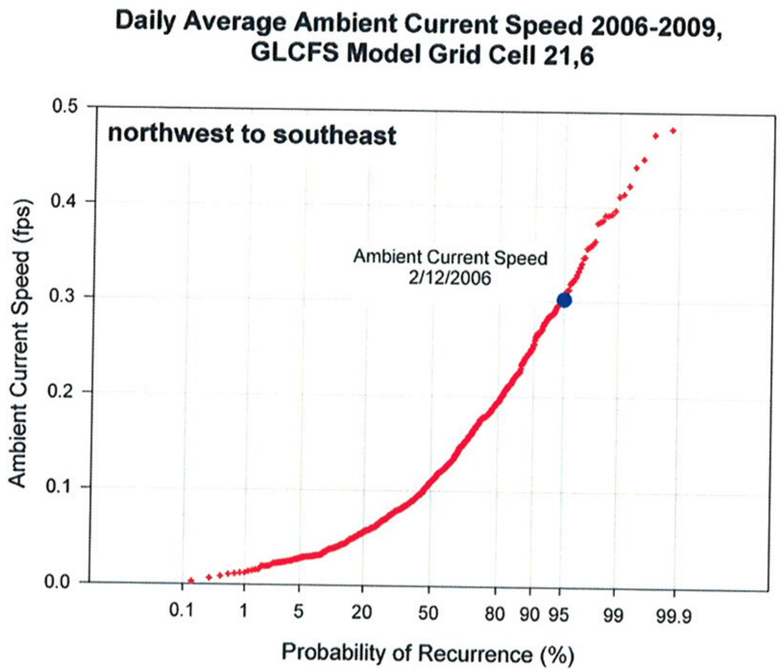


Figure 4-1. Probability of Recurrence for Alternative Meteorological Conditions



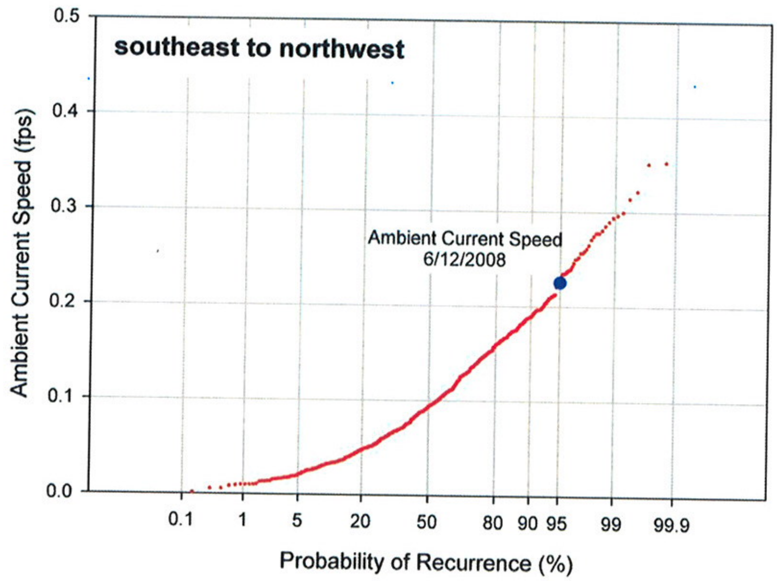


Figure 4-2. Probability of Recurrence for Alternative Ambient Current Directions

In order to simulate a range of scenarios, various conditions were coordinated. This was accomplished by using all of the meteorological conditions from a single day as opposed to looking at extreme cases for each component of the meteorological conditions. Macro-scale circulation patterns in Lake Michigan are driven by wind and near the outfall southeast to northwest currents are generally associated with winds blowing from the south. Conversely, northwest to southeast currents are generally associated with winds blowing from the north. These relationships have been maintained in the various simulated scenarios that have been used to evaluate the predicted likely maximum extent of the thermal plume. In total, eight scenarios were evaluated in the model and these are summarized in Table 4-1.

Table 4-1. Summary of Extreme Scenarios

Scenario	Plant Operations	Meteorological Conditions	Wind Direction	Current Direction
1	existing	spring	from north	to southeast
2	existing	spring	from south	to northwest
3	existing	summer	from north	to southeast
4	existing	summer	from south	to northwest
5	proposed	spring	from north	to southeast
6	proposed	spring	from south	to northwest
7	proposed	summer	from north	to southeast
8	proposed	summer	from south	to northwest

Where:

Plant Operations

existing = 96.4 mgd, 1.7E+09 Btu/hr
proposed =81.76 mgd, 1.7E+09 Btu/hr

Meteorological Conditions

spring = meteorological conditions observed over the 24 hour period of April 4, 2008;
difference: daily average air temperature and daily average water temperature = +4.7 F
summer = meteorological conditions observed over the 24 hour period of August 2, 2007;
daily average temperature = 81.7 F

Wind Direction

from north (spring) = variable wind speed April 4, 2008
from north (summer) = variable wind speed August 2, 2007
from south (spring) = variable wind speed, from April 4, 2008
with wind direction reversed to blow from south direction
from south (summer) = variable wind speed, from August 2, 2007,
with wind direction reversed to blow from south direction

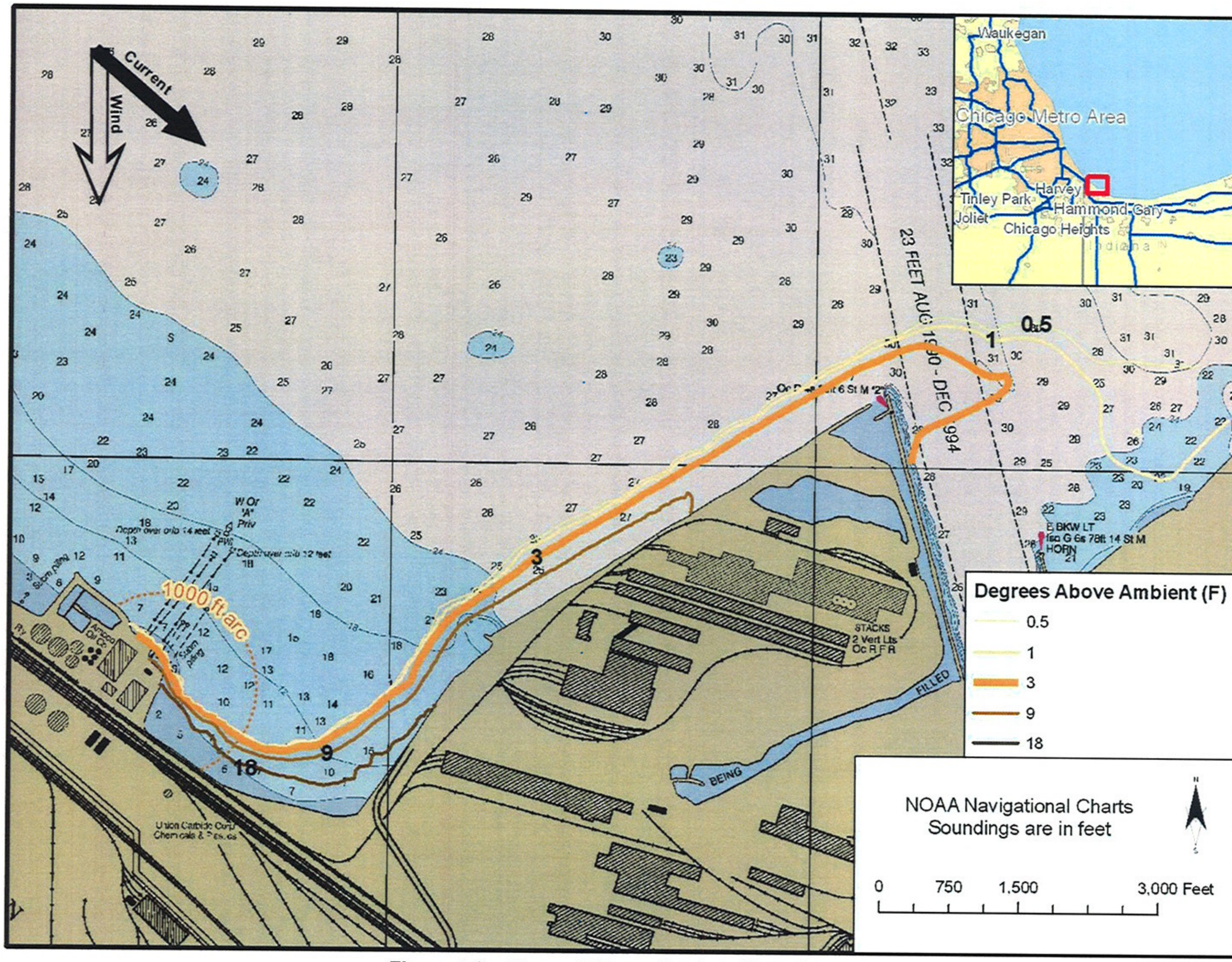
Current Direction

to southeast = dominant current direction towards southeast; current speed = 0.30 fps
to northwest = dominant current direction towards northwest; current speed = 0.23 fps

All of the scenarios use the appropriate conditions based on Table 4-1 for a full twenty four hour period. That period is then repeated for a total scenario time period of fifteen days in order to establish a stable thermal plume. The plume for each scenario was delineated once stable conditions were reached.

4.2 Predicted Extent of Thermal Plume

This section provides the predicted extent of the thermal plume under each scenario described above. The thermal plume is defined by the extent of the thermal discharge. The delta temperature value (degrees above ambient) in each case is determined by applying each scenario within the model and comparing it to the same scenario without the plant in operation. For each scenario, the extent of the thermal surface plume is presented in Figure 4-3. Table 4-2 summarizes the thermal plume excursion at the surface, at the mid depth, and at the bottom of the water column. The distance is measured from the discharge location and follows the centerline of the plume show in the Figure 4-3.



Scenario 1:
Plant Operations: existing
Met Conditions: spring
Wind Direction: from north
Current Direction: to southeast

Figure 4-3a. Thermal Plume Contour Maps for All Scenarios

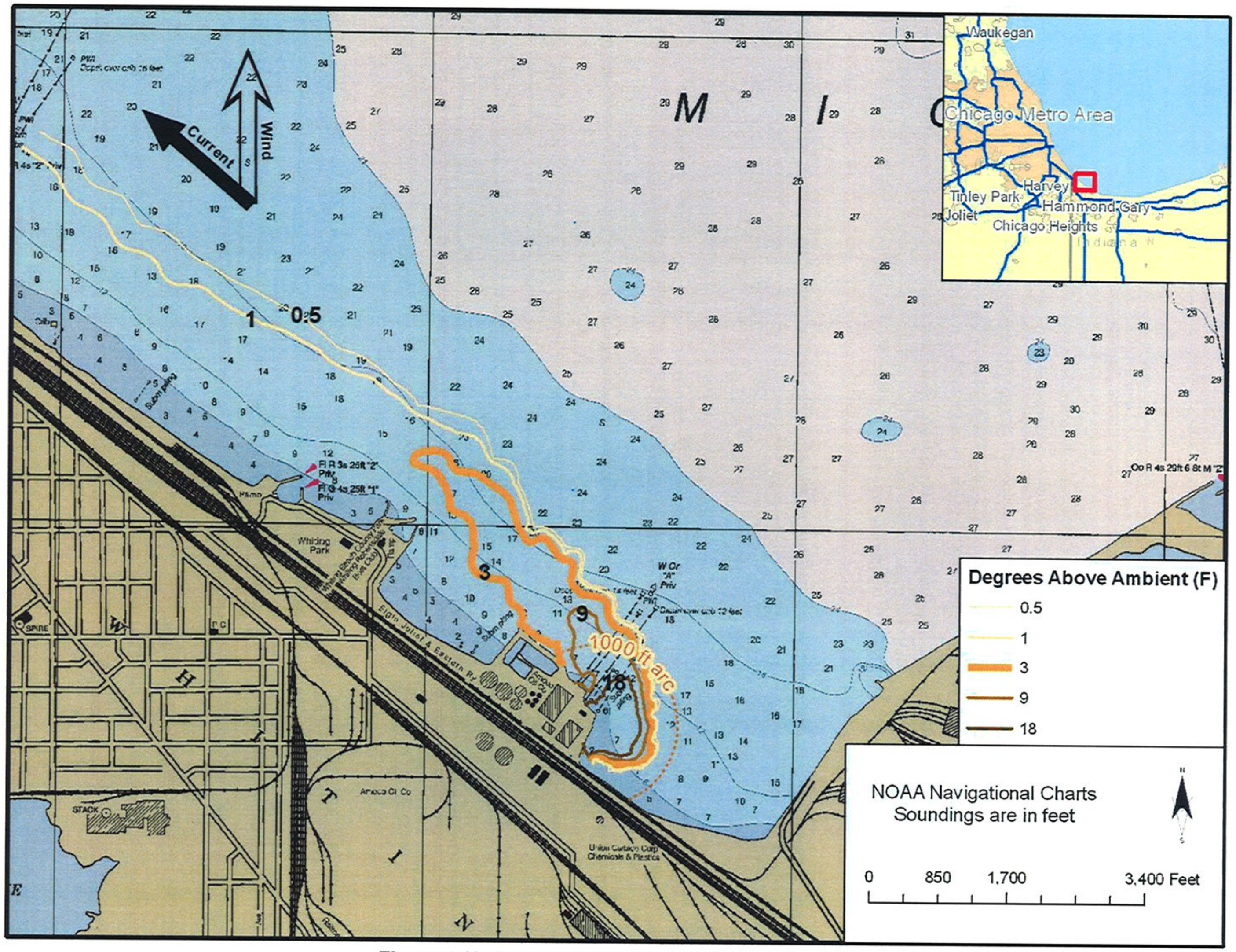


Figure 4-3b. Thermal Plume Contour Maps for All Scenarios

Scenario 2:
Plant Operations: existing
Met Conditions: spring
Wind Direction: from south
Current Direction: to northwest

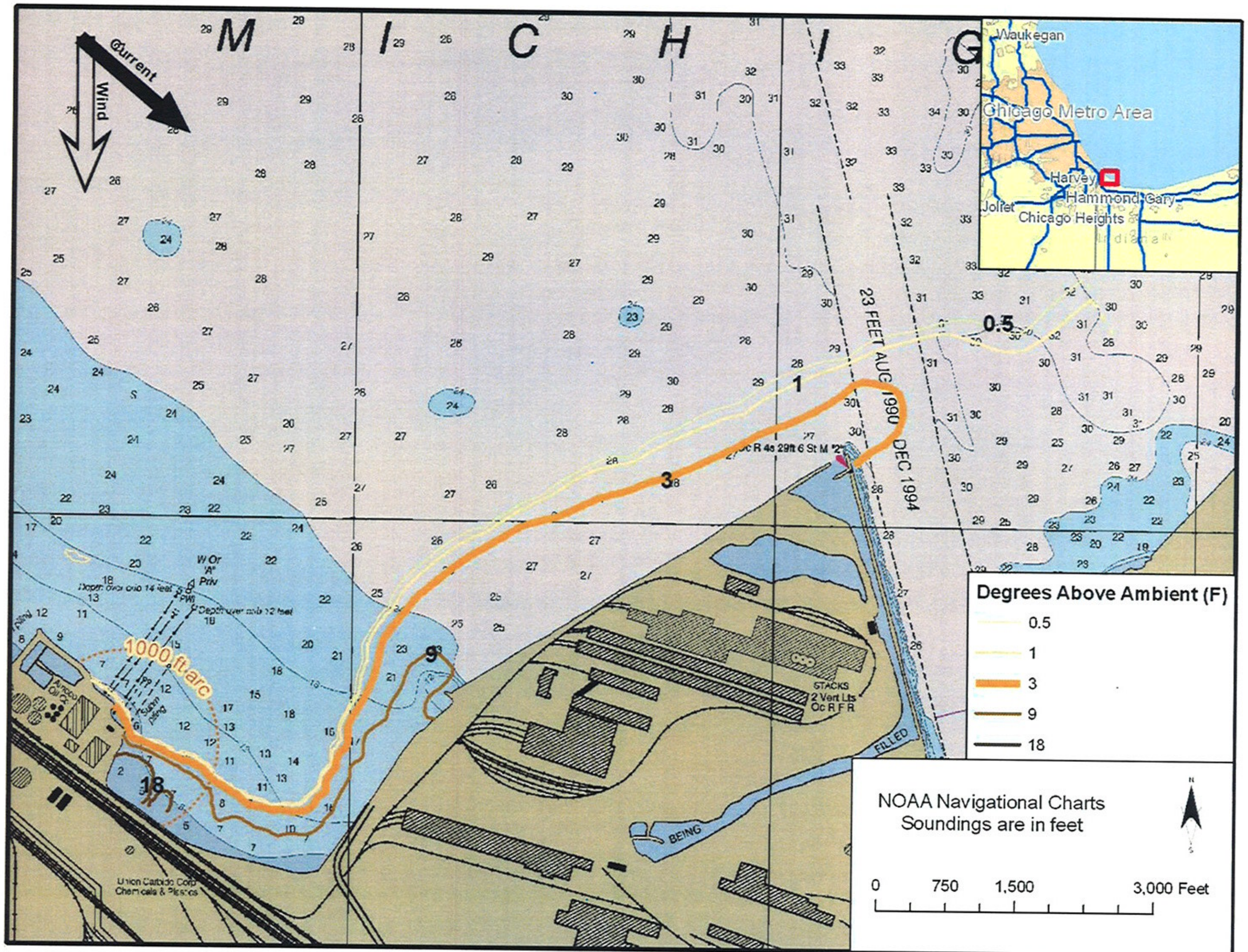


Figure 4-3c. Thermal Plume Contour Maps for All Scenarios

Scenario 3:
Plant Operations: Existing
Met Conditions: summer
Wind Direction: from north
Current Direction: to southeast

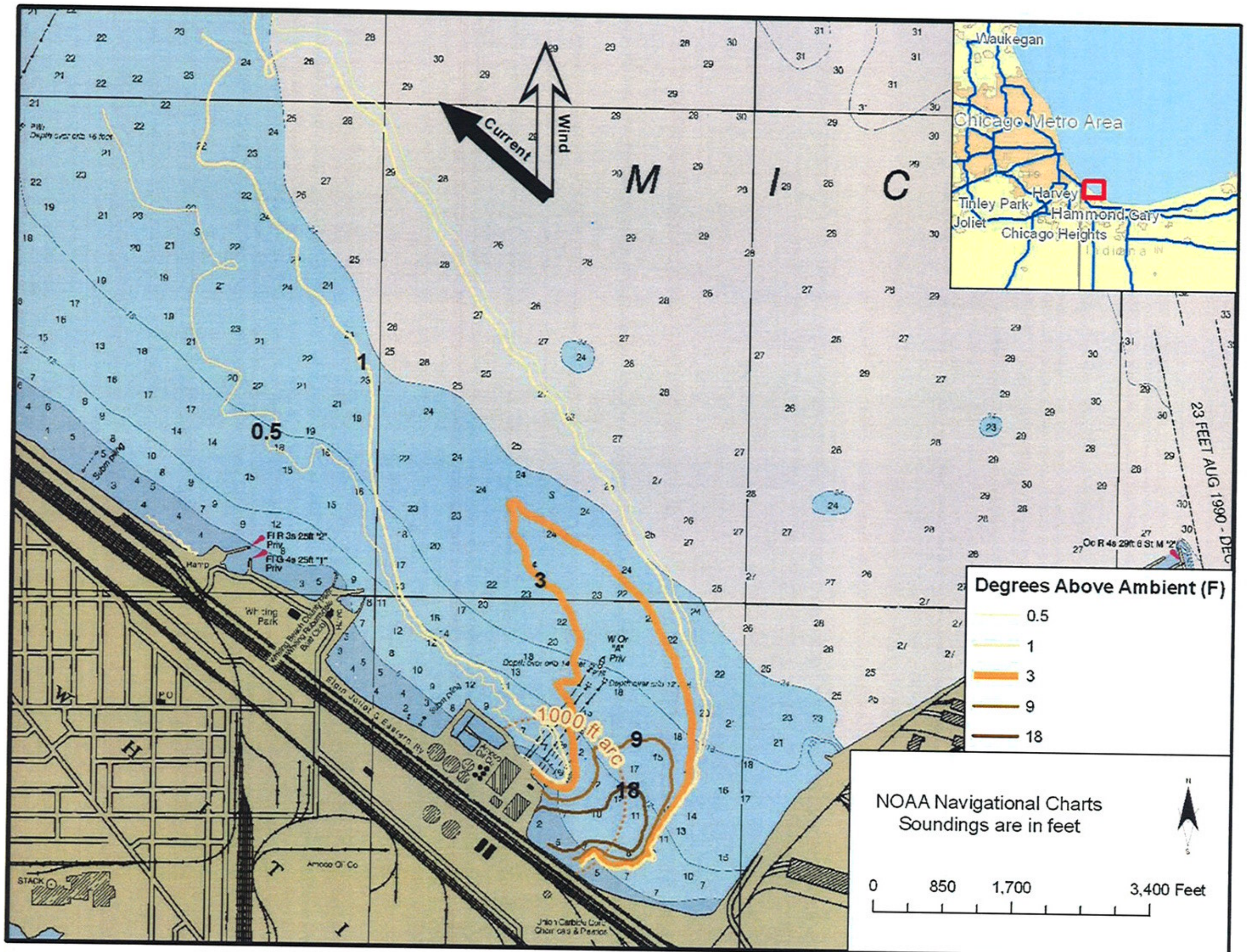
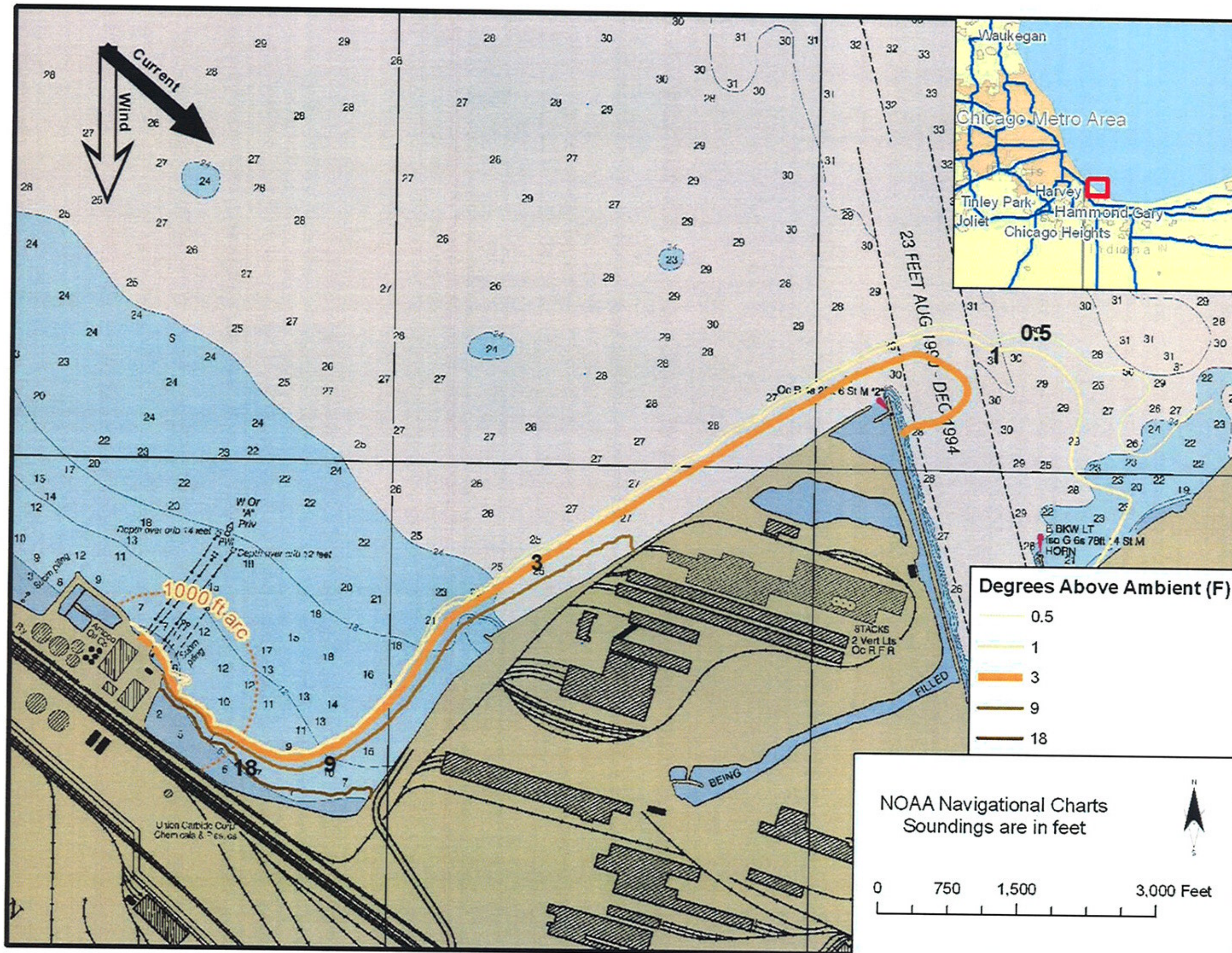


Figure 4-3d. Thermal Plume Contour Maps for All Scenarios

Scenario 4:
Plant Operations: Existing
Met Conditions: summer
Wind Direction: from south
Current Direction: to northwest



Scenario 5:
Plant Operations: proposed
Met Conditions: spring
Wind Direction: from north
Current Direction: to southeast

Figure 4-3e. Thermal Plume Contour Maps for All Scenarios

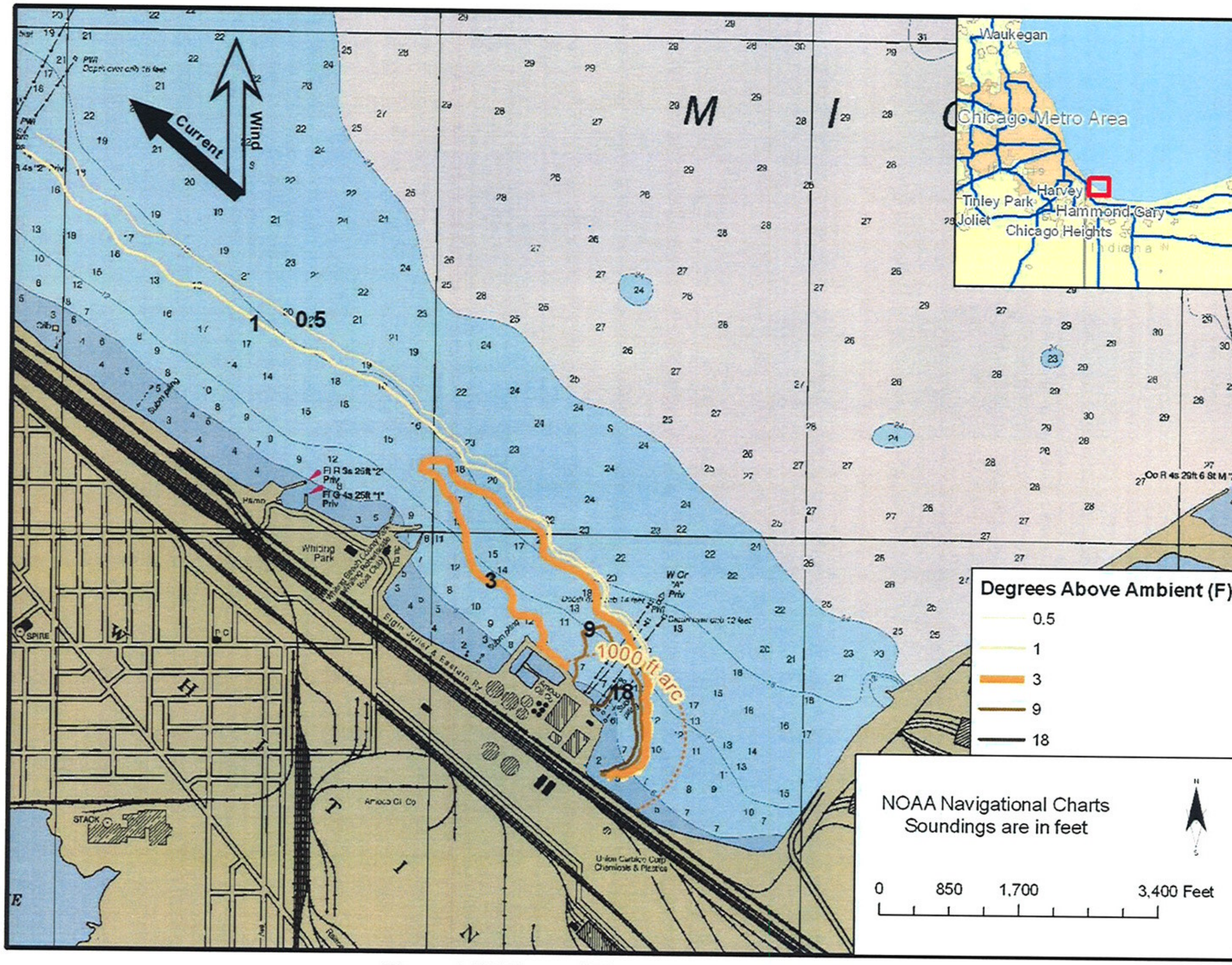


Figure 4-3f. Thermal Plume Contour Maps for All Scenarios

Scenario 6:
Plant Operations: proposed
Met Conditions: spring
Wind Direction: from south
Current Direction: to northwest

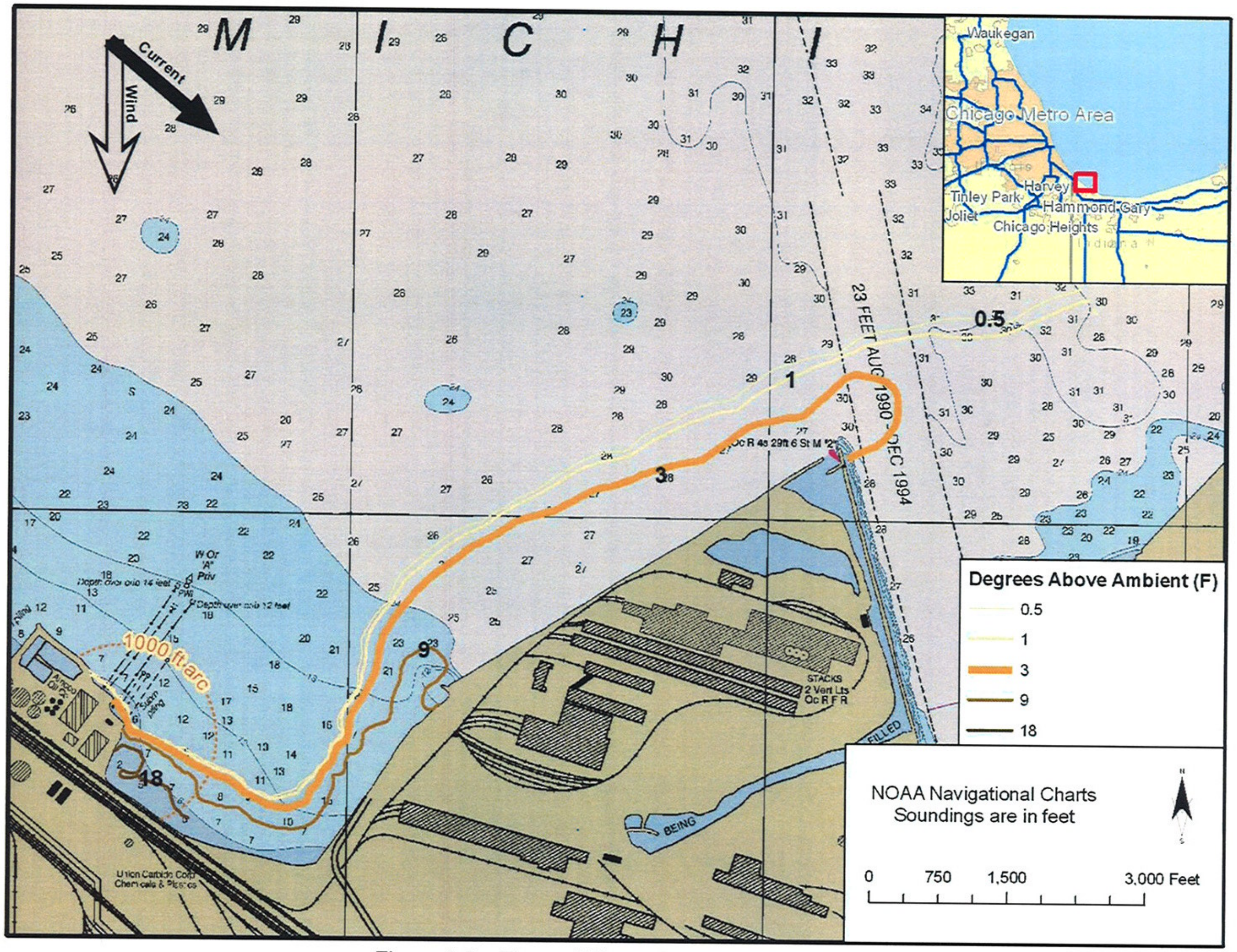
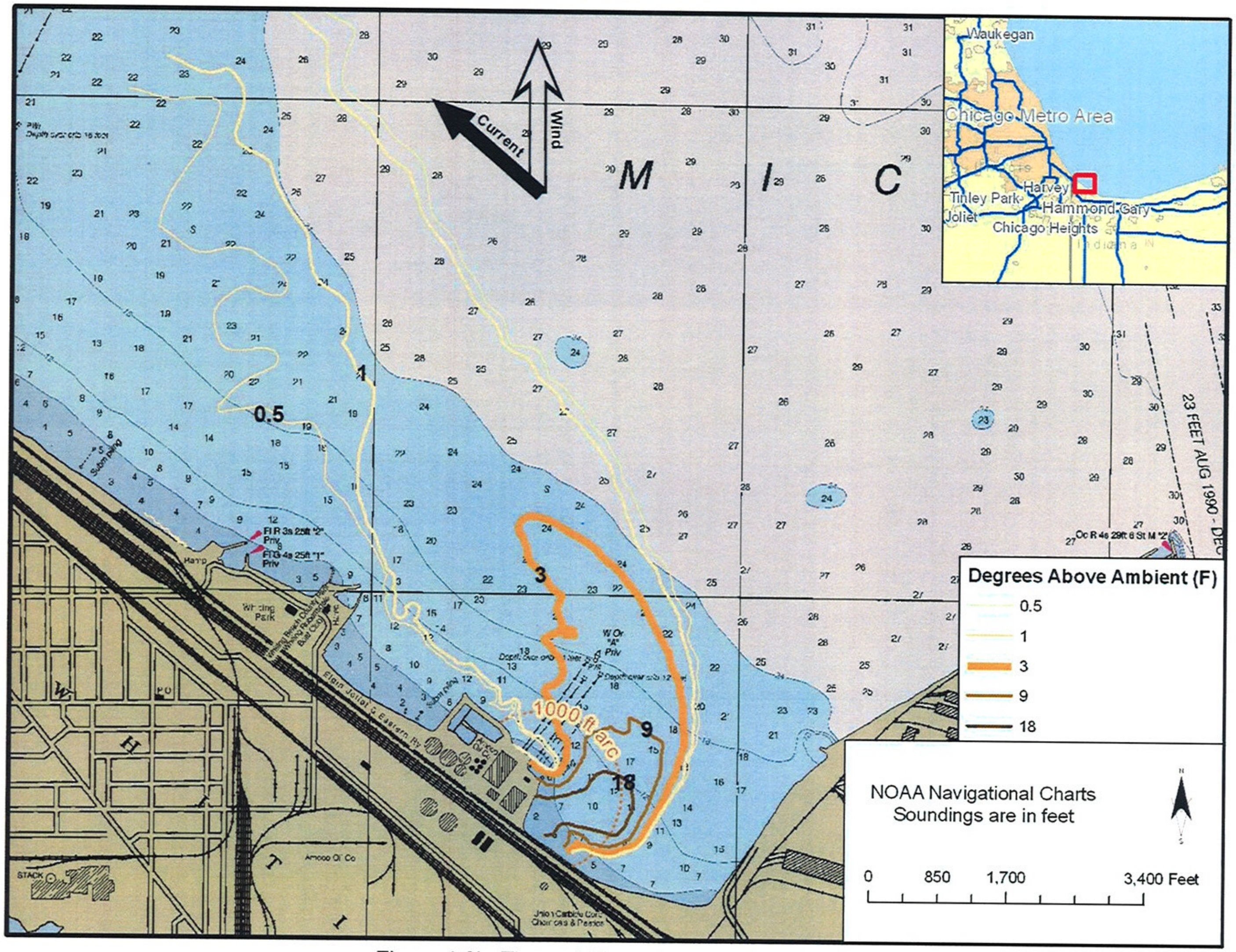


Figure 4-3g. Thermal Plume Contour Maps for All Scenarios

Scenario 7:
Plant Operations: Proposed
Met Conditions: summer
Wind Direction: from north
Current Direction: to southeast



Scenario 8:
Plant Operations: Proposed
Met Conditions: summer
Wind Direction: from south
Current Direction: to northwest

Figure 4-3h. Thermal Plume Contour Maps for All Scenarios

Table 4-2. Multiple Depth Extent of Thermal Plume

Scenario	Surface Extent (ft)	Mid Depth Extent (ft)	Bottom Depth Extent (ft)
1	10,600	2,800	2400
2	6,000	800	250
3	10,000	2,650	150
4	6,450	550	150
5	10,100	2,800	2,400
6	4,540	800	250
7	10,000	2,650	150
8	4,900	550	150

According to Indiana minimum surface water quality criteria governing temperature in Lake Michigan [327 IAC 2-1.5-8 (c)], the receiving water temperature cannot be 3 degrees Fahrenheit greater than existing background temperature at a maximum distance of 1,000-foot arc encircling the thermal discharge. The area within the arc can exceed the standard. In addition, the receiving water temperature outside the arc cannot exceed the maximum allowable temperatures in Lake Michigan, shown in Table 4-3, except when the ambient water temperature (intake temperature) is already within three degrees or greater than the maximum allowable temperature in Lake Michigan.

Table 4-3. Lake Michigan Maximum Water Temperatures Outside of the 1,000-foot Arc

Month	Temperature (F)[A]
January	45
February	45
March	45
April	55
May	60
June	70
July	80
August	80
September	80
October	65
November	60
December	50

A: 327 IAC 2-1.5-8(c)(4)(D)(iv)(BB)(aa)

Based on the predicted surficial extent of the thermal plume and extent at other depths, under extreme conditions the BP Whiting Refinery plume exceeds the 1,000-foot mixing zone arc that surrounds the plant discharge location. This finding is supported by the reconnaissance data collected during the field program which indicated a greater than three degree increase in water temperatures outside of the 1,000-foot arc. The extent of the thermal plume is not predicted to differ significantly under the proposed future discharge scenario. The extent of the thermal plume is greatest when wind is from the north and ambient current directions are towards the southeast. The plume travels along the shoreline of Lake Michigan and effectively reaches the Indiana Harbor Canal before the flow of water from the Indiana Harbor Canal dilutes the thermal plume, resulting in temperature increases that are less than 3 F, resulting in a length along the center line of the plume of approximately 10,000 feet.

The maximum allowable water temperature according to state water quality standards (Table 4-3) are surpassed outside of the 1,000-foot arc in both the spring (April) and summer (August) scenarios. In spring scenarios surface temperatures do not return to below maximum allowable temperatures until a distance of 6,400 feet along the center line of the plume and in the summer scenarios, the surface temperatures do not return to below the maximum allowable temperatures until a distance of 10,400 feet along the center line of the plume.

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5.0 Conclusion

BP has conducted a thermal plume study of its once-through cooling water discharge in accordance with the study plan approved by IDEM. This study constitutes the Phase 1 of the 316(a) variance demonstration. The objectives of the thermal plume study are to characterize the size and areal extent of the thermal plume under worst-case scenarios based on its current discharge limits. The thermal effluent study established the relationship of end-of-pipe discharge temperature and temperature at the 1,000-foot arc. A field survey was implemented to collect site-specific temperature and current data. A 3-D EFDC model was calibrated and validated using the field data.

The calibrated and validated model was used to predict the extent of the thermal plume under a range of worst-case scenarios. The worst case scenarios include summer time (warm) conditions and spring time (cool) conditions. The two seasonal variations were evaluated under both north-northwest ambient water currents and south-southeast ambient water current conditions. The same scenarios were evaluated for the existing configuration of the BP Whiting plant and for the proposed future conditions.

The results of model scenario runs indicate that the thermal plumes exceed the 1,000-foot arc encircling the outfall under worst-case scenarios. The proposed plant conditions are not expected to have a significant impact on the extent of the thermal plume. The extent of the thermal plume is greatest when wind is from the north and ambient current directions are towards the southeast.

Based on the thermal plume study results, a 316(a) variance demonstration is warranted. BP will prepare a proposed 316(a) variance demonstration plan (Phase 2) in response to IDEM's comments on the biological assessment and seek IDEM's approval. Once IDEM approves, BP will implement the Phase 2 study in 2011. This demonstration would update the 1975 variance study and be submitted along with the 2012 NPDES permit renewal application.

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